

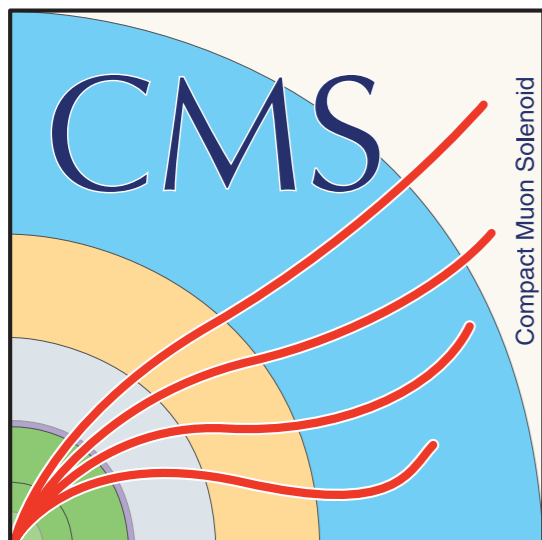
Status of direct searches for top-quark partners at the LHC

today: vector-like quarks



Johannes Erdmann
TU Dortmund

on behalf of the ATLAS and CMS Collaborations



A First Glance Beyond the Energy Frontier
Trieste, 08.09.2016



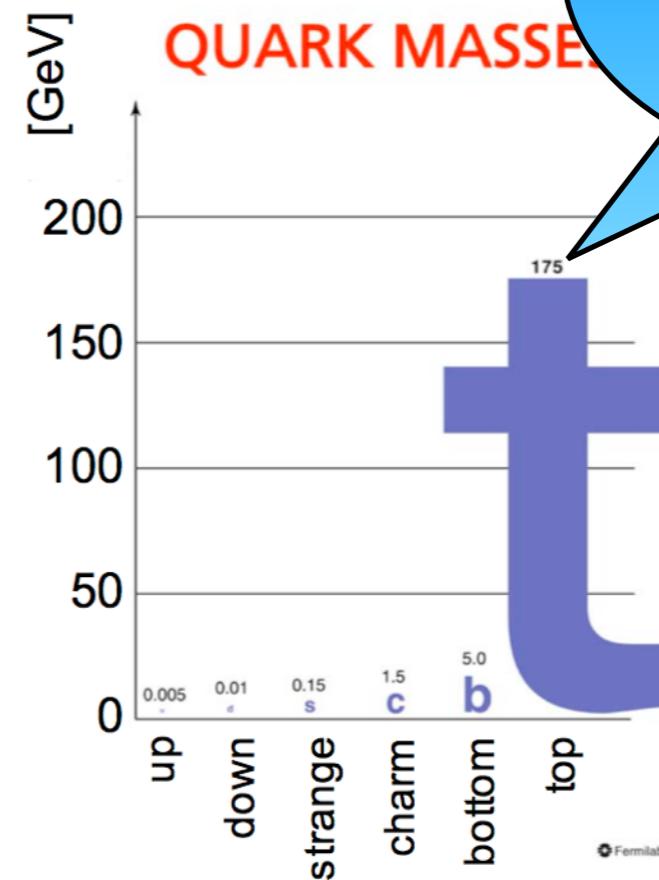
Outline

- Brief introduction
- Status after Run-1
- Overview status Run-2
 - Pair production
 - Single production*incl. remarks on **BOOST** techniques*
- Conclusions



ElitePartner

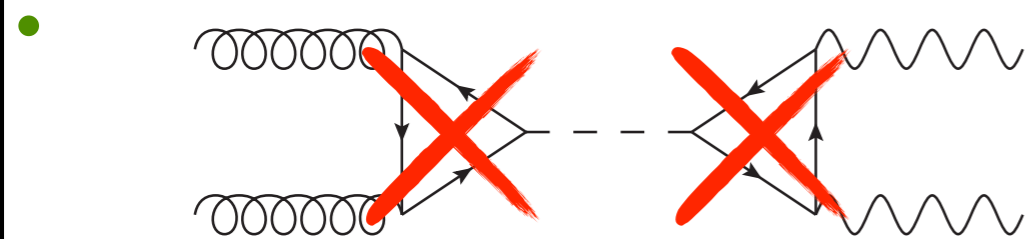
**Looking for a partner
5—10 x heavier
(+ rich & famous)**



Spoiler alert !
→ *No new physics
found, yet.*

Chiral 4th Quark Generation

- excluded by Higgs discovery

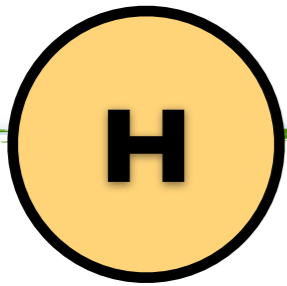


Vector-like quarks (VLQ)

- LH and RH same SU(2) transformation
 - direct mass term allowed : $m\bar{\psi}\psi$
- mix with SM quarks
- multiplets w/ SU(3)xSU(2)xU(1) quantum no.

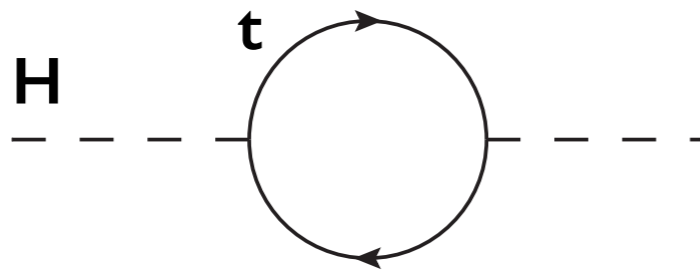
	VLQ	Q [e]	T3
singlets	(T) (B)	+2/3 -1/3	0
doublets	(X,T) (T,B) (B,Y)	+5/3, +2/3 +2/3, -1/3 -1/3, -4/3	$\pm 1/2$
triplets	(X,T,B) (T,B,Y)	+5/3, +2/3, -1/3 +2/3, -1/3, -4/3	+1, 0, -1

Composite H, Little H, ...



The Higgs is special

- only known elementary scalar
- Δm_H quadratically divergent



→ *Perhaps not elementary ?*

- (pseudo-)Nambu-Goldstone boson of new strongly interacting sector ?
- VLQ predicted with $m \approx O(2 \text{ TeV})$
 - indirect constraints exist, but model dependent — need direct searches !

**new
strong
sector**



?

**more
bound
states?**



?

VLQ



TeV

Higgs

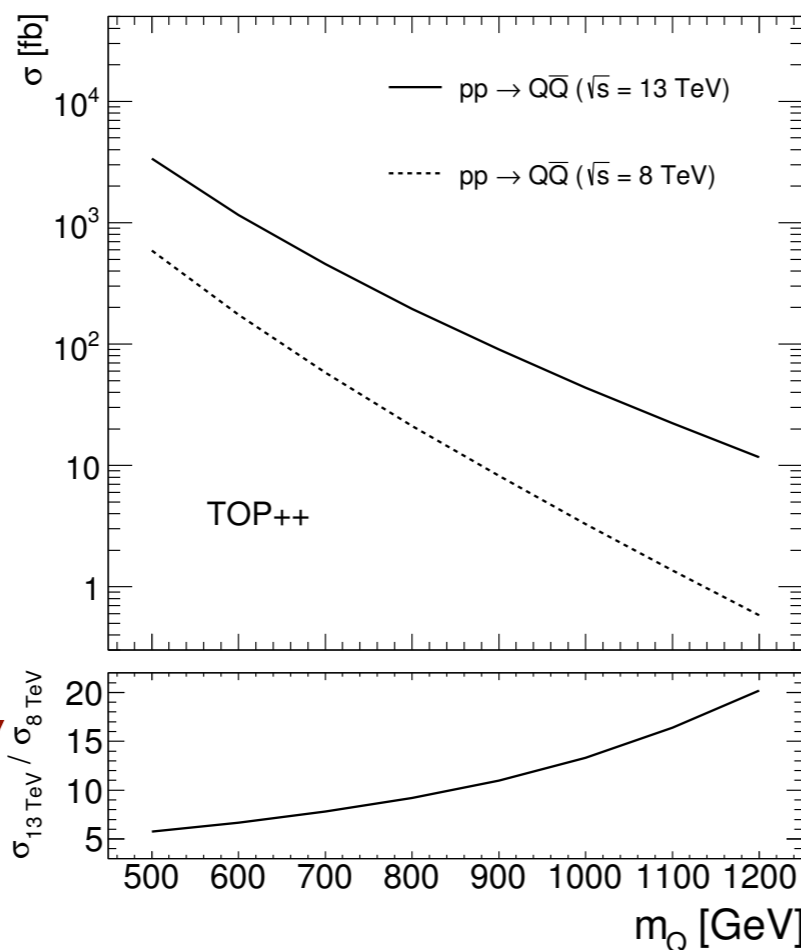
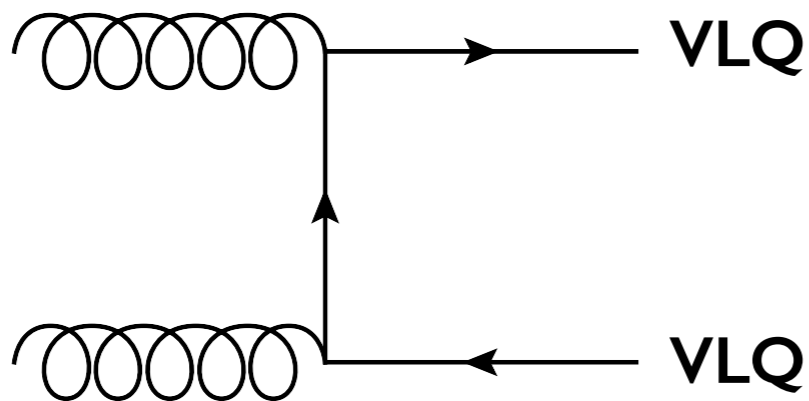


vev



Pair Production & VLQ Decay

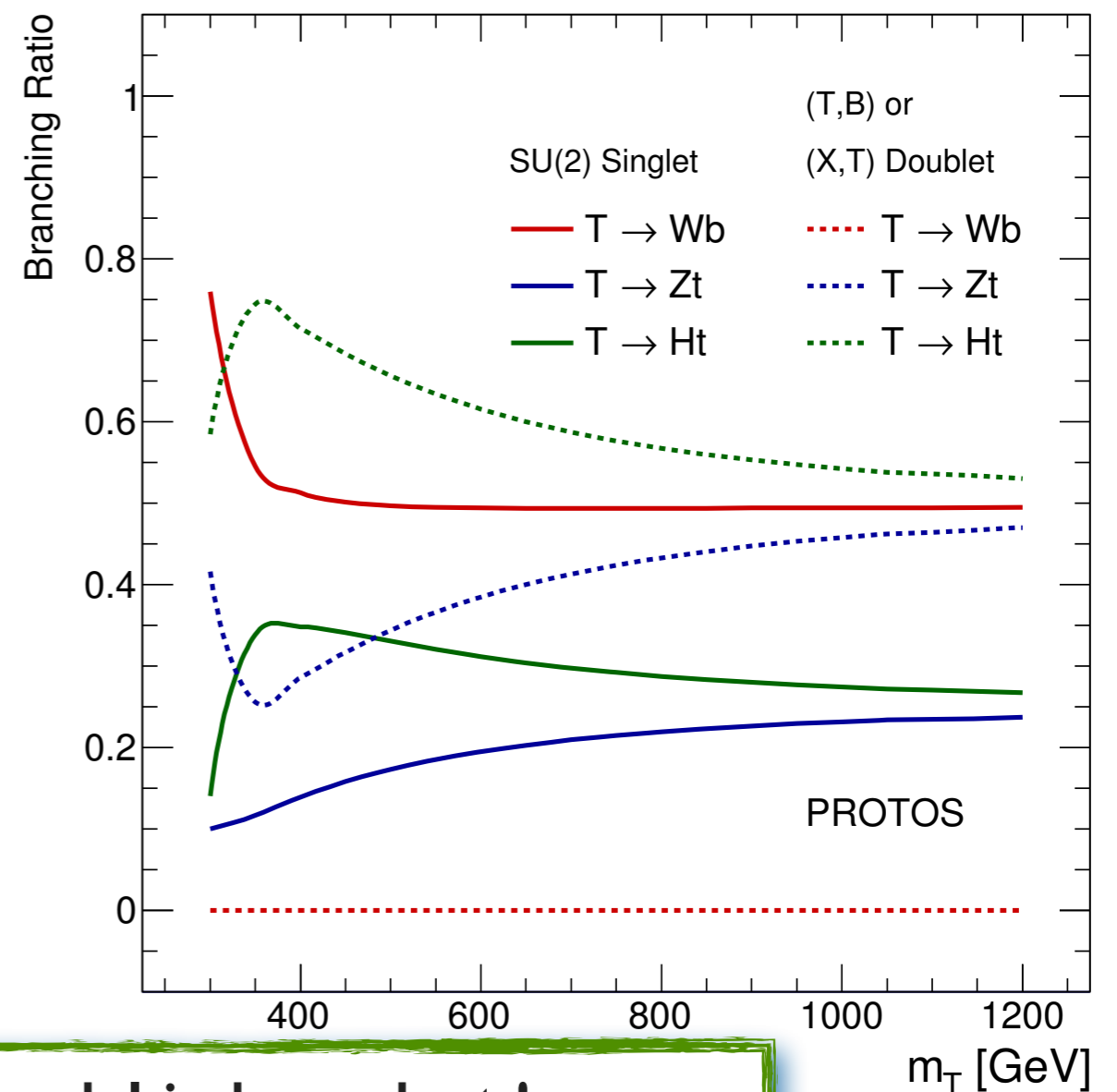
Strong pair production



σ increases strongly for 13 TeV

Decay

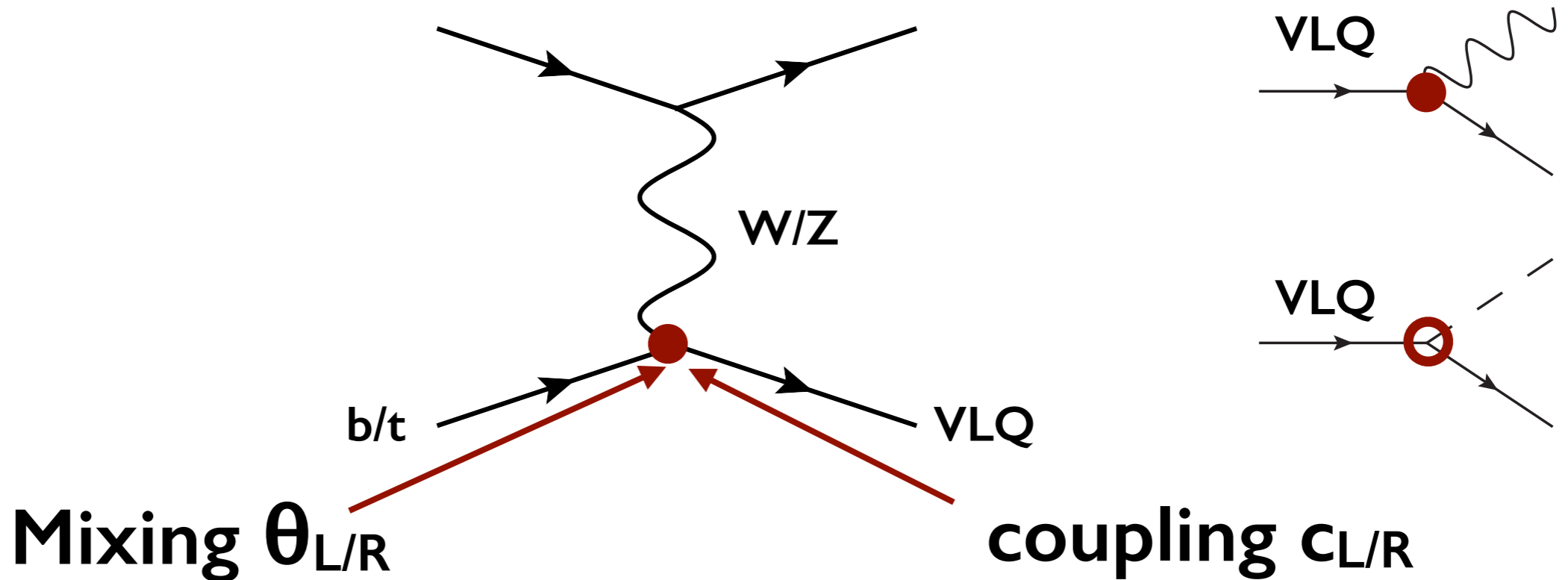
- assume : only coupling to 3rd gen.
- VLQ \rightarrow t/b + W/Z/H
- BRs given by multiplet



Strong production — model-independent !

(decay kinematics may be different for different couplings)

Single Production



$$\begin{pmatrix} t_{L,R} \\ T_{L,R} \end{pmatrix} = U_{L,R}^u \begin{pmatrix} t_{L,R}^0 \\ T_{L,R}^0 \end{pmatrix} = \begin{pmatrix} \cos \theta_{L,R}^u & -\sin \theta_{L,R}^u e^{i\phi_u} \\ \sin \theta_{L,R}^u e^{-i\phi_u} & \cos \theta_{L,R}^u \end{pmatrix} \begin{pmatrix} t_{L,R}^0 \\ T_{L,R}^0 \end{pmatrix}$$

(Aguilar-Saavedra, Benbrik, Heinemeyer, Perez-Victoria, Phys. Rev. D 88 (2013) 094010)

Mixing angles not independent

→ LH/RH dominates in each multiplet

$$\sigma_{\text{sing}}(X\bar{t}) = \left[(c_L^{XV})^2 + (c_R^{XV})^2 \right] \sigma_{V\bar{t}}(M_X) + c_L^{XV} c_R^{XV} \left(\frac{m_t}{M_X + m_t} \right) \sigma'_{V\bar{t}}(M_X),$$

$$\sigma_{\text{sing}}(X\bar{b}) = \left[(c_L^{XV})^2 + (c_R^{XV})^2 \right] \sigma_{V\bar{b}}(M_X),$$

$$\sigma_{\text{sing}}(\bar{X}t) = \left[(c_L^{XV})^2 + (c_R^{XV})^2 \right] \sigma_{\bar{V}t}(M_X) + c_L^{XV} c_R^{XV} \left(\frac{m_t}{M_X + m_t} \right) \sigma'_{\bar{V}t}(M_X),$$

$$\sigma_{\text{sing}}(\bar{X}b) = \left[(c_L^{XV})^2 + (c_R^{XV})^2 \right] \sigma_{\bar{V}b}(M_X).$$

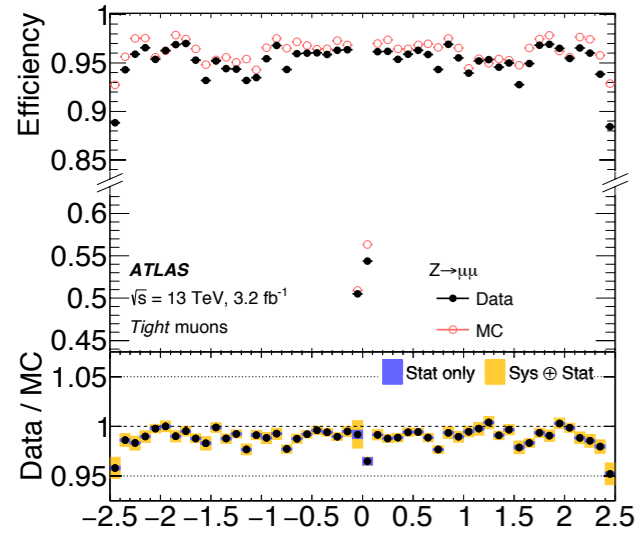
(Matsedonskyi, Panico, Wulzer, JHEP 12 (2014) 097;
also: Buchkremer, Cacciapaglia, Deandrea, Panizzi, Nucl. Phys. B 876 (2013) 376)

$$\tan \theta_R^q = \frac{m_q}{m_Q} \tan \theta_L^q \quad (\text{singlets, triplets}),$$

$$\tan \theta_L^q = \frac{m_q}{m_Q} \tan \theta_R^q \quad (\text{doublets}),$$

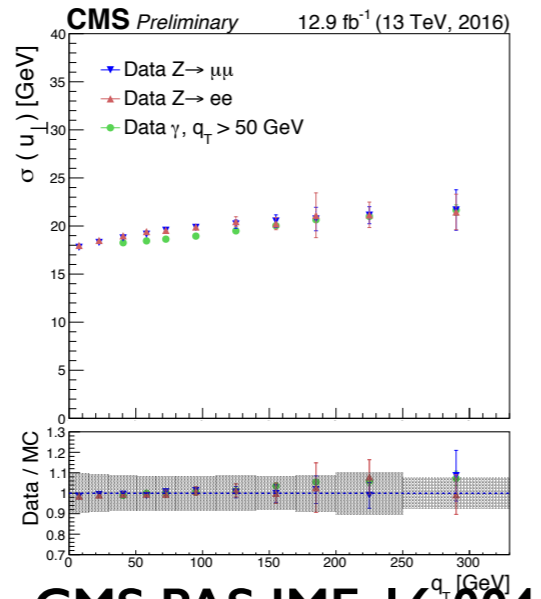
Experimental Challenges

Leptons



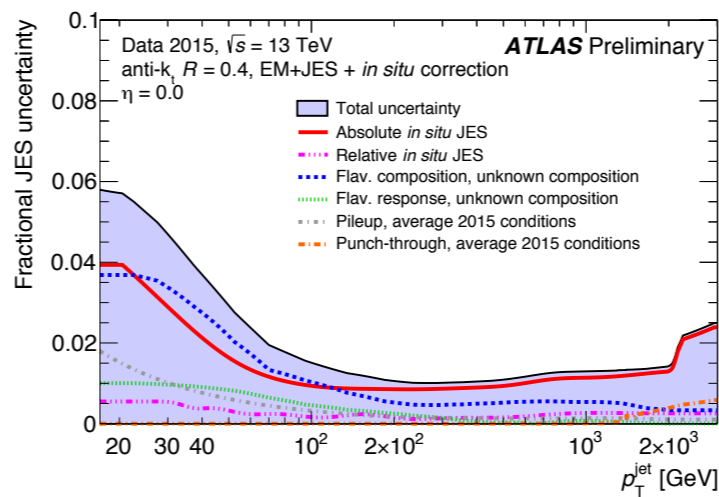
EPJC 76 (2016) 292

MET

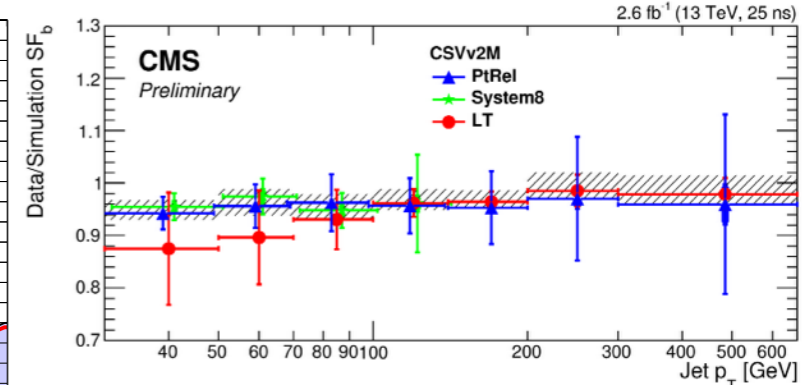


CMS PAS JME-16-004
44m

Jets

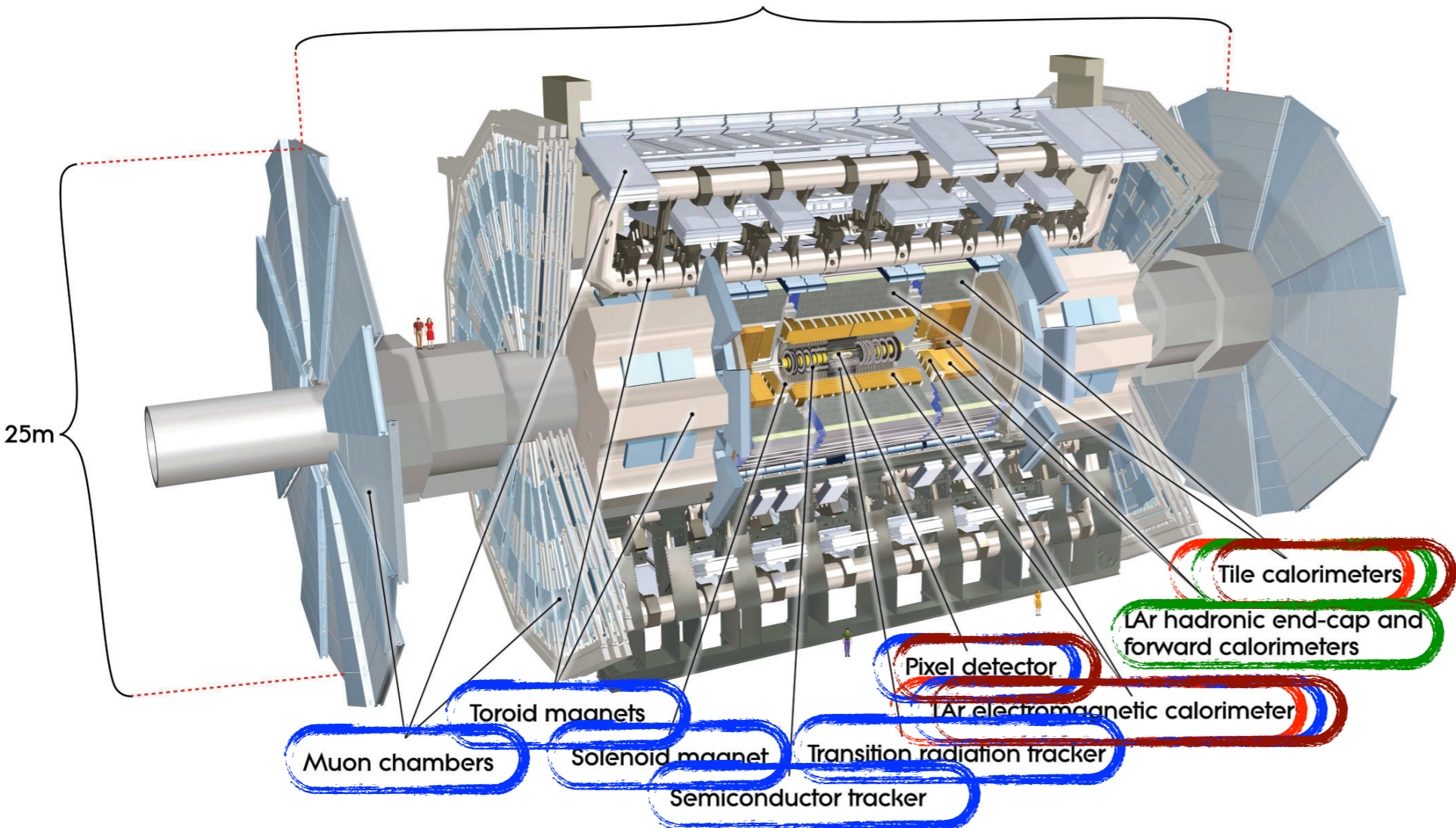


b-tags



CMS PAS BTV-15-001

Impressed
tourist pic



Status Quo after Run-I

CMS Searches for New Physics Beyond Two Generations (B2G)

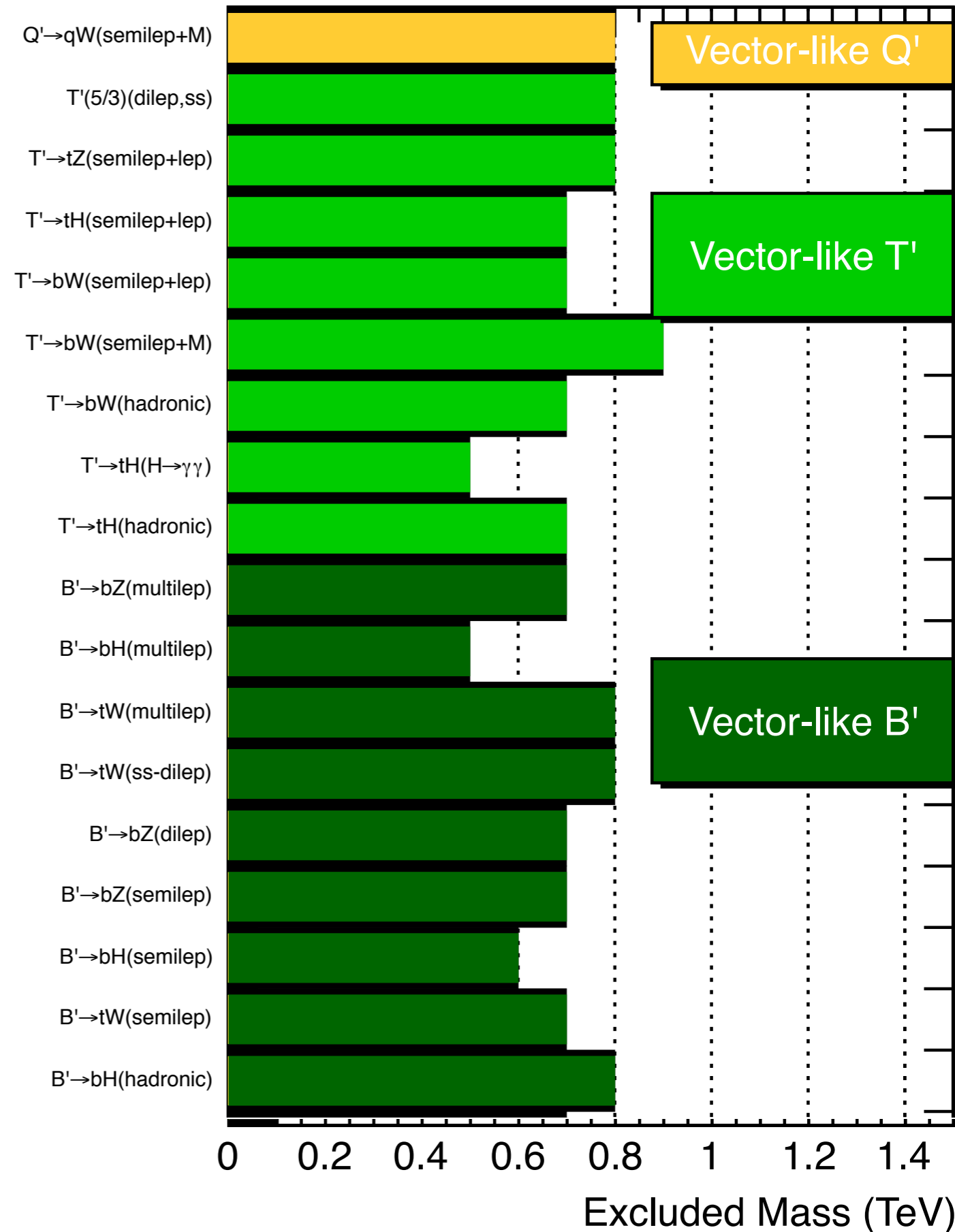
95% CL Exclusions (TeV)

- Extensive search program for pairs
- Mass limits from ~ 700 to ~ 900 GeV
- Depend on assumed BRs

ATLAS example : (JHEP 08 (2015) 105)

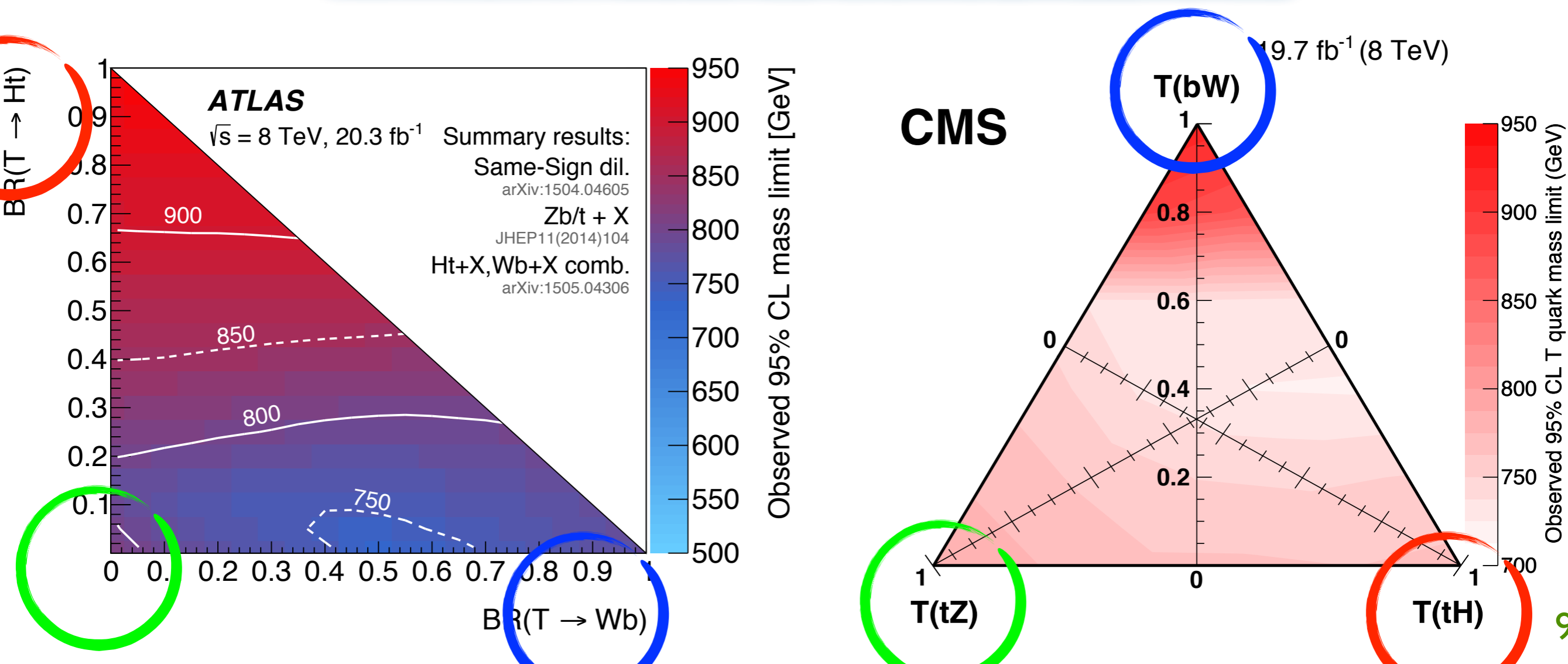
singlet T: $m > 765$ GeV

doublet T: $m > 855$ GeV

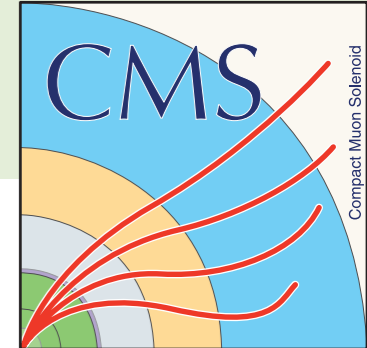


Run-I Strategies

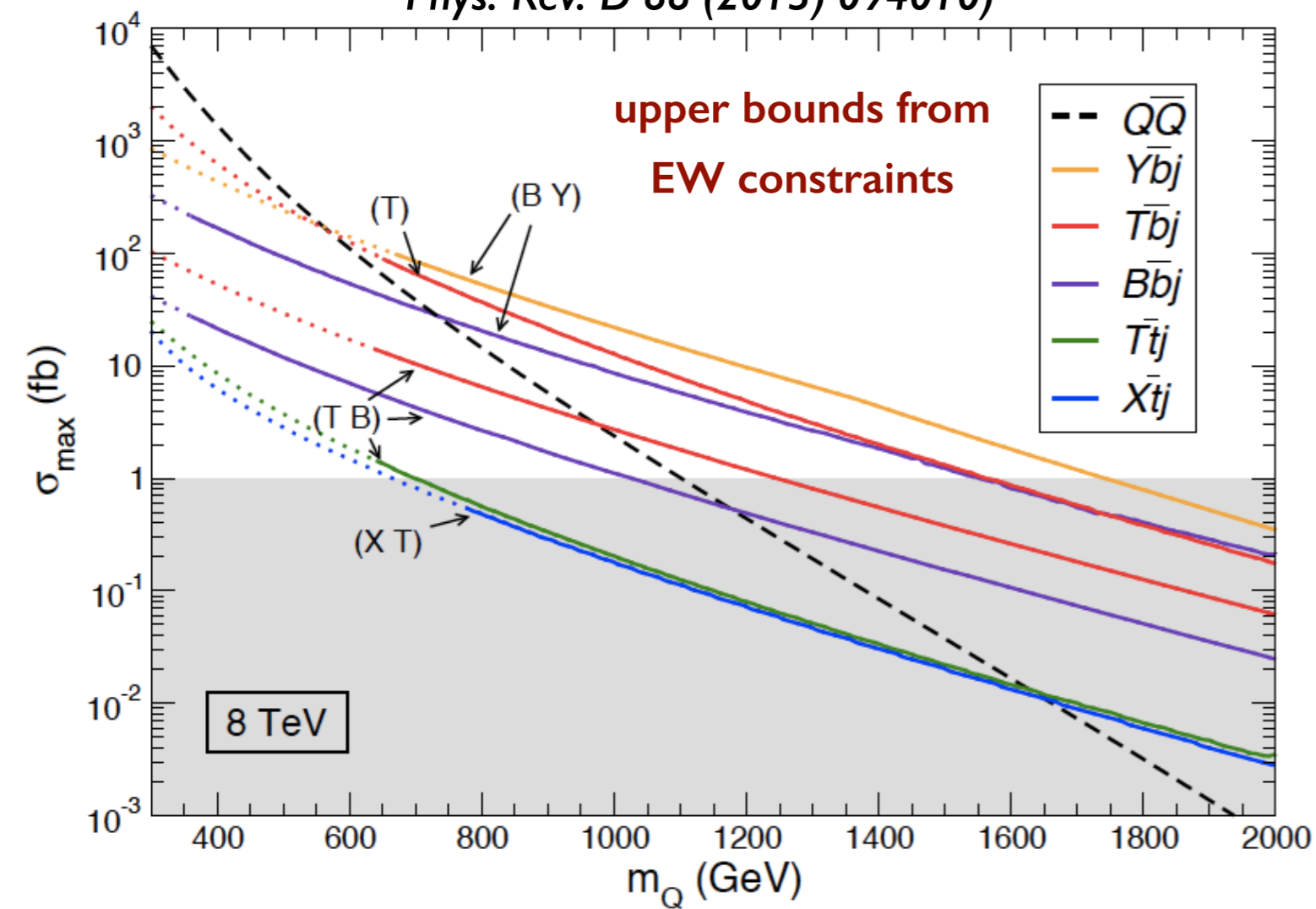
- σ dominated by pair production
- Focus on decay to 3rd gen.
- Exploiting the full *BR triangle*
- ATLAS strategy inclusive ('TT \rightarrow Ht+X')
- CMS strategy more exclusive ('TT \rightarrow bWbW')
- combination papers (*PRD 93 (2016) 012003* and *112009*)



Single Production @ Run-I

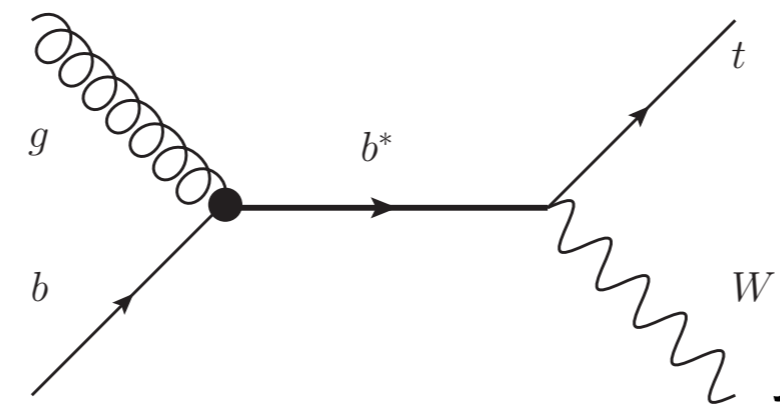


(Aguilar-Saavedra, Benbrik, Heinemeyer, Perez-Victoria,
Phys. Rev. D 88 (2013) 094010)



- Pair production dominates for $m < \sim 1$ TeV
- EW single production may dominate at high m

Single production may be enhanced (here: excited b)



JHEP 01 (2016) 166

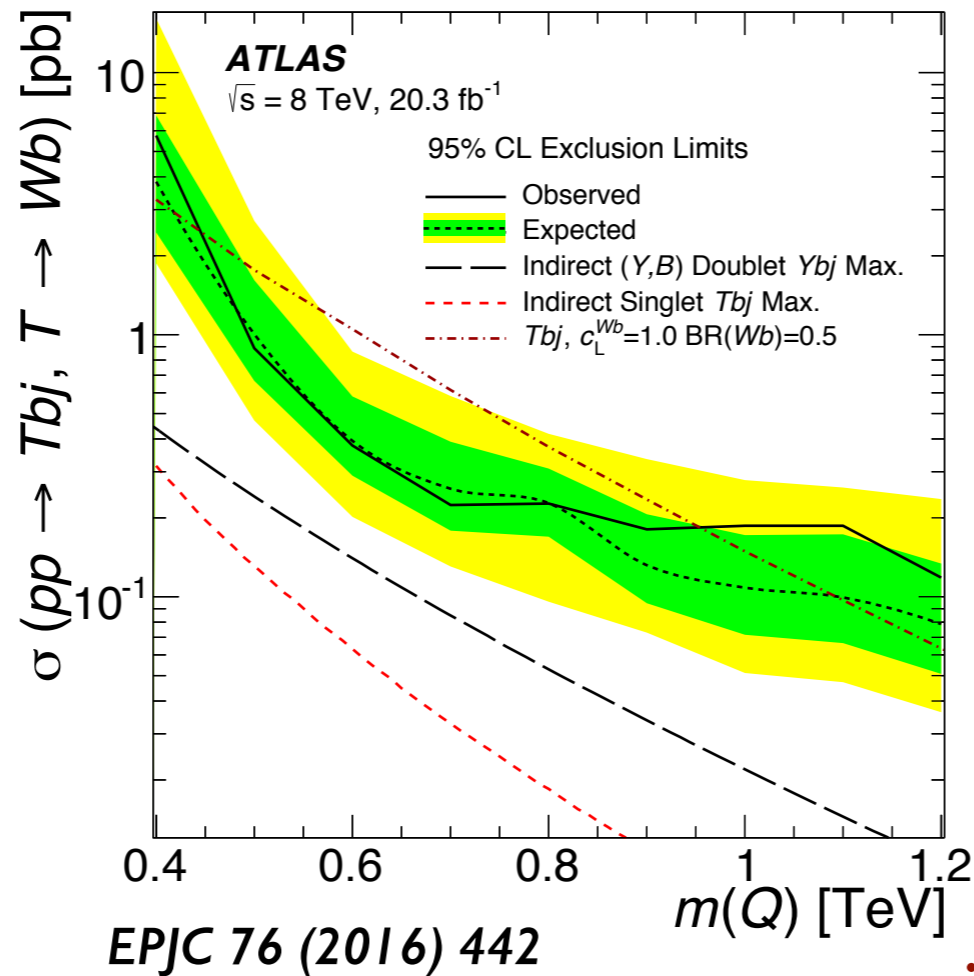
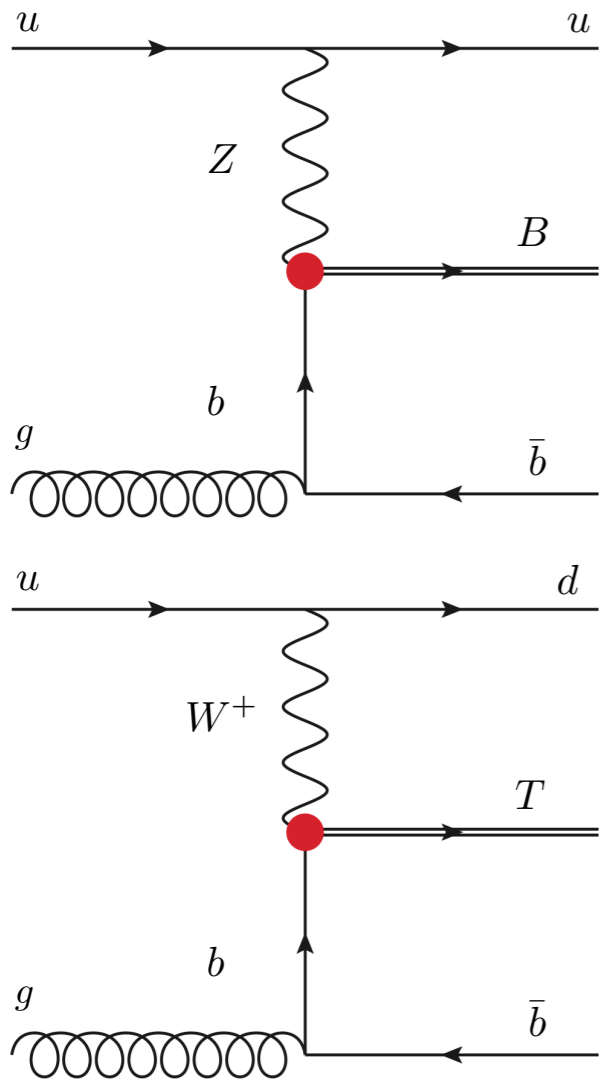
Single Production @ Run-I

Sensitivity to single production challenging at 8 TeV

low σ for EW

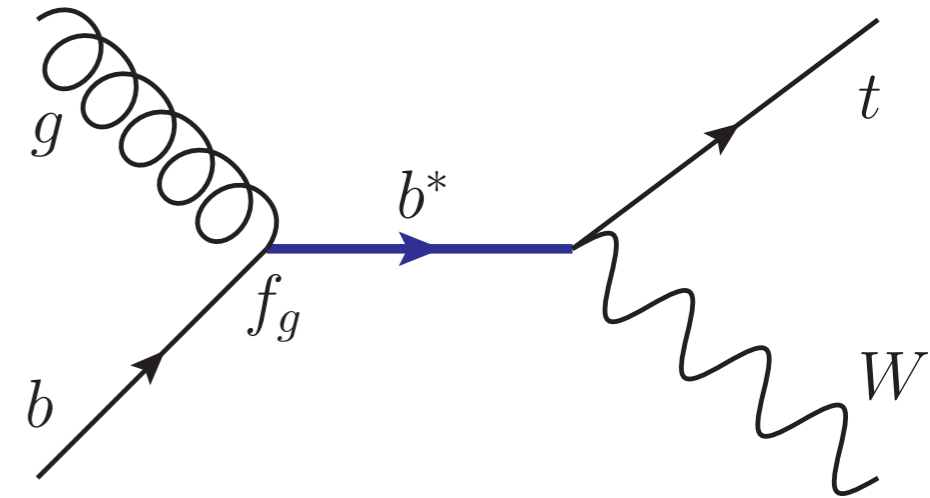
with large coupling

JHEP 11 (2014) 104
also JHEP 02 (2016) 110

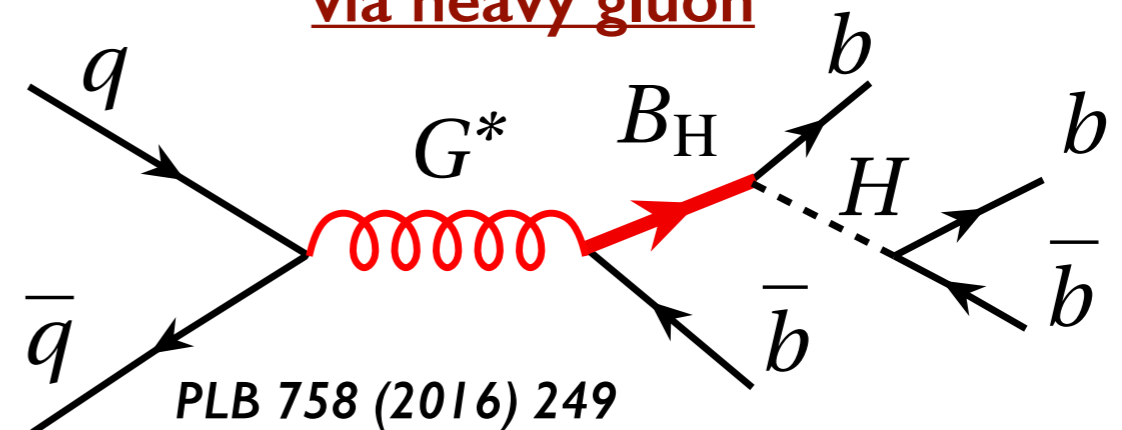


excited b-quark

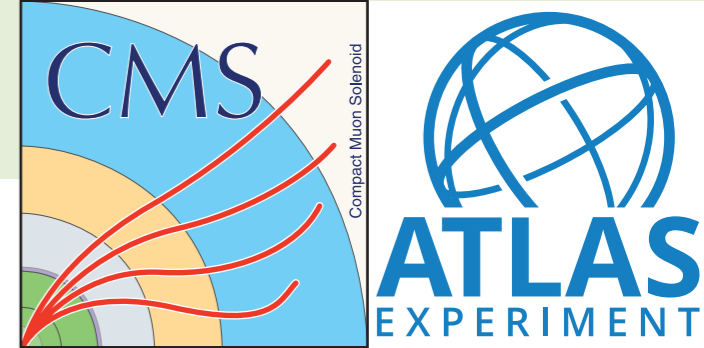
JHEP 02 (2016) 110



via heavy gluon

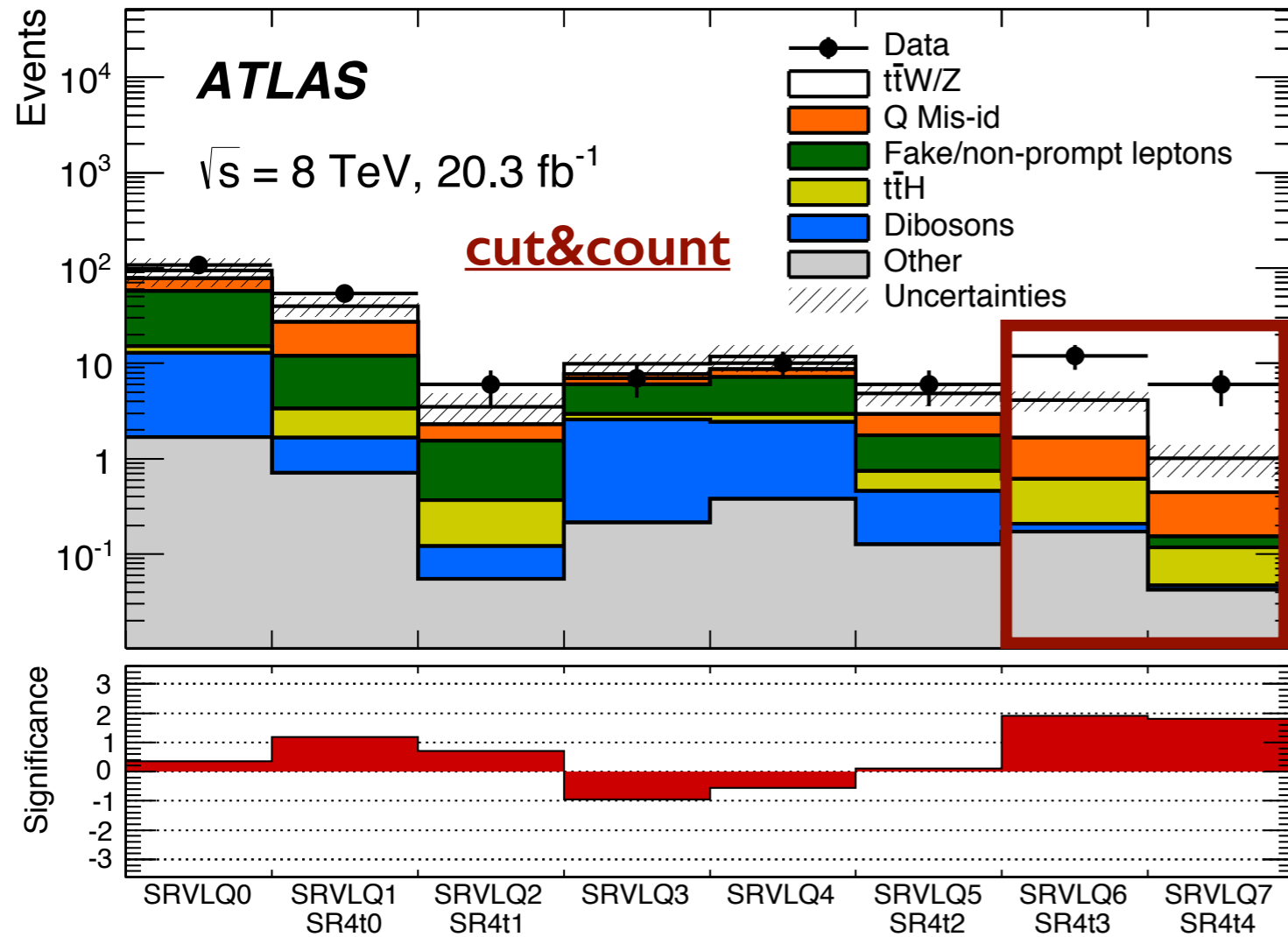


Some Excitement @ Run-I



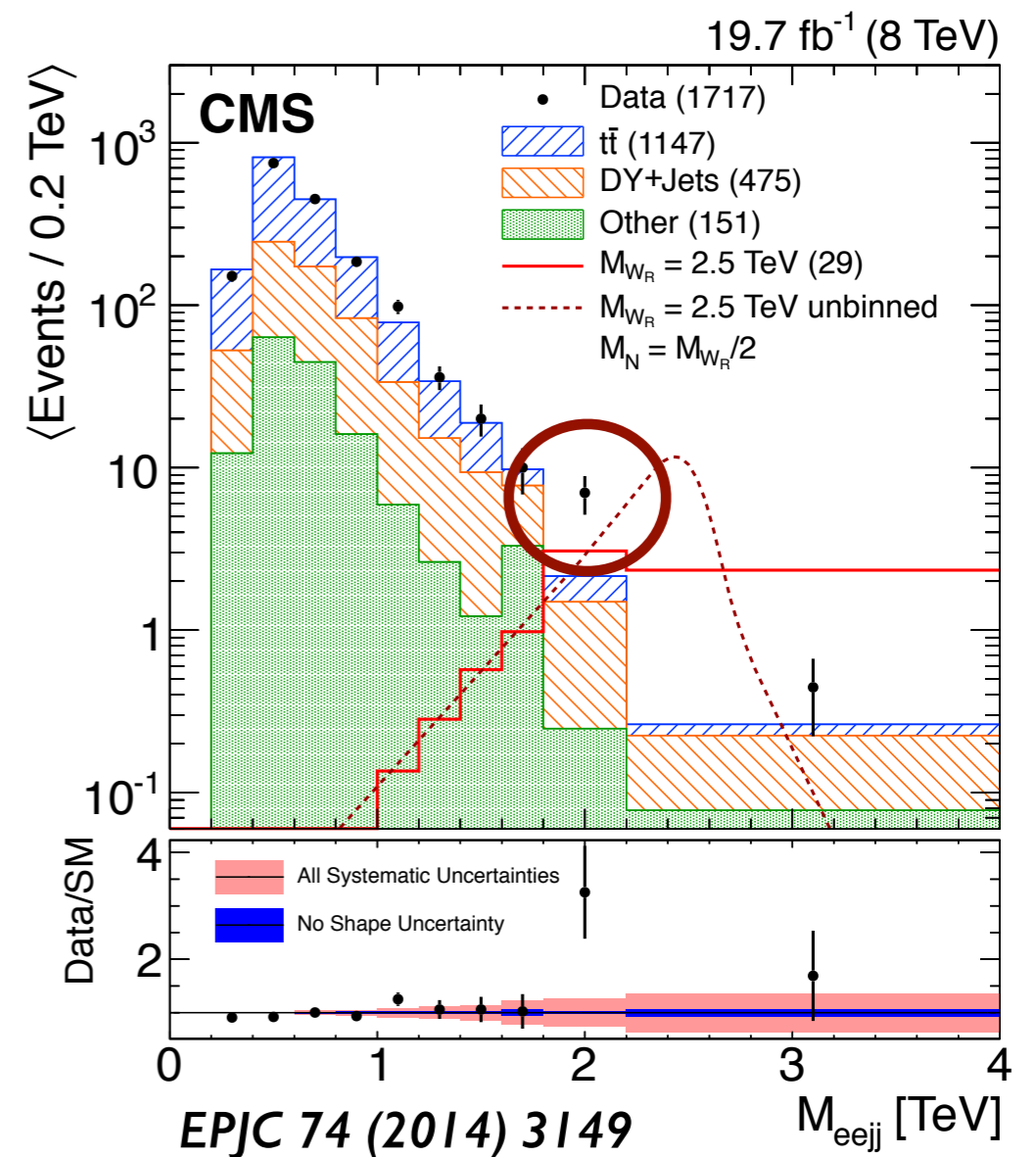
Same-sign leptons + b-quarks

JHEP 10 (2015) 150



Link to other Run-I excesses?

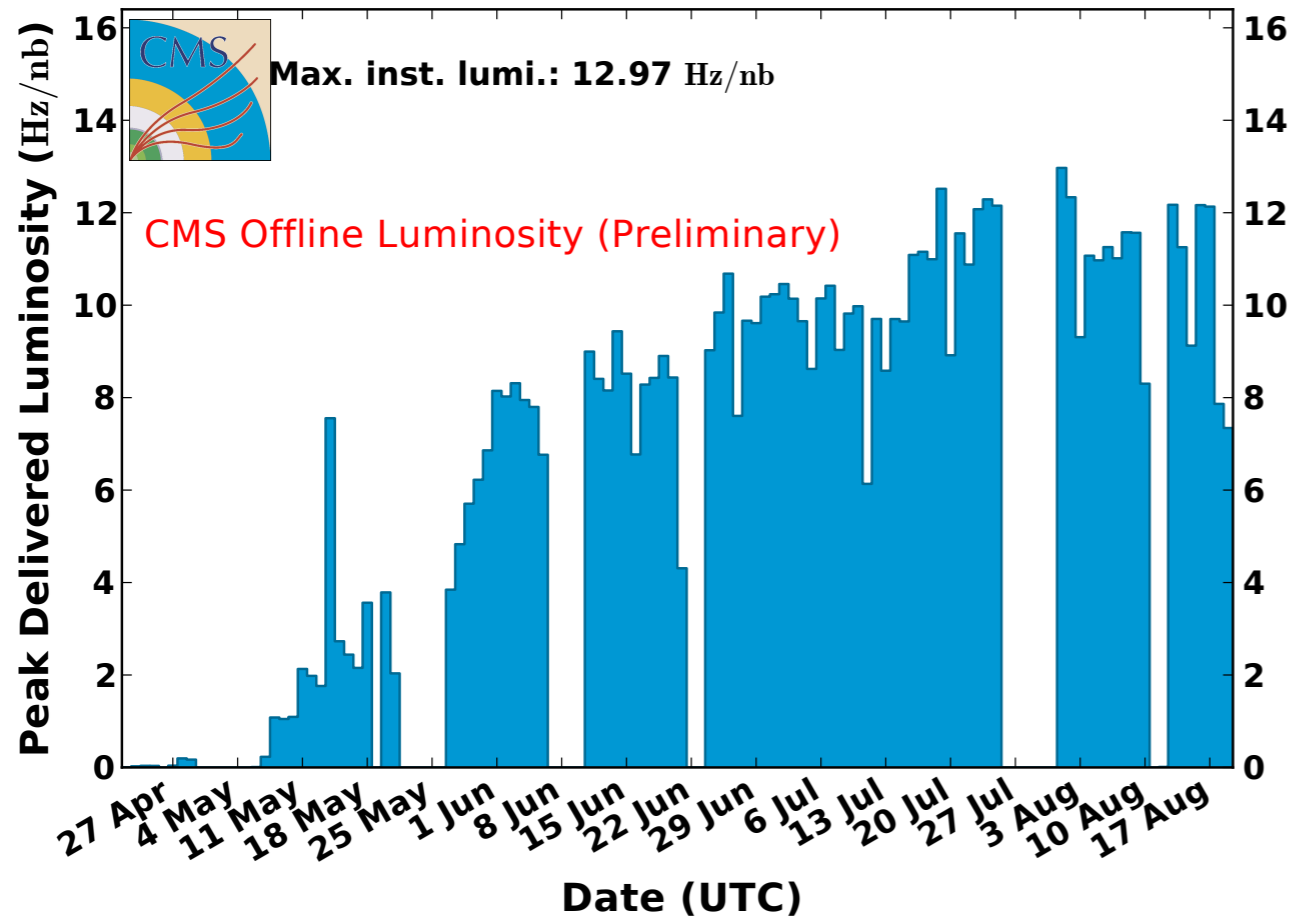
(just one ex. Dobrescu, Liu, JHEP 10 (2015) 118
propose $W' \rightarrow H^+ A^0 / H^0 \rightarrow t\bar{b}t\bar{t}$)



From 8 TeV to 13 TeV

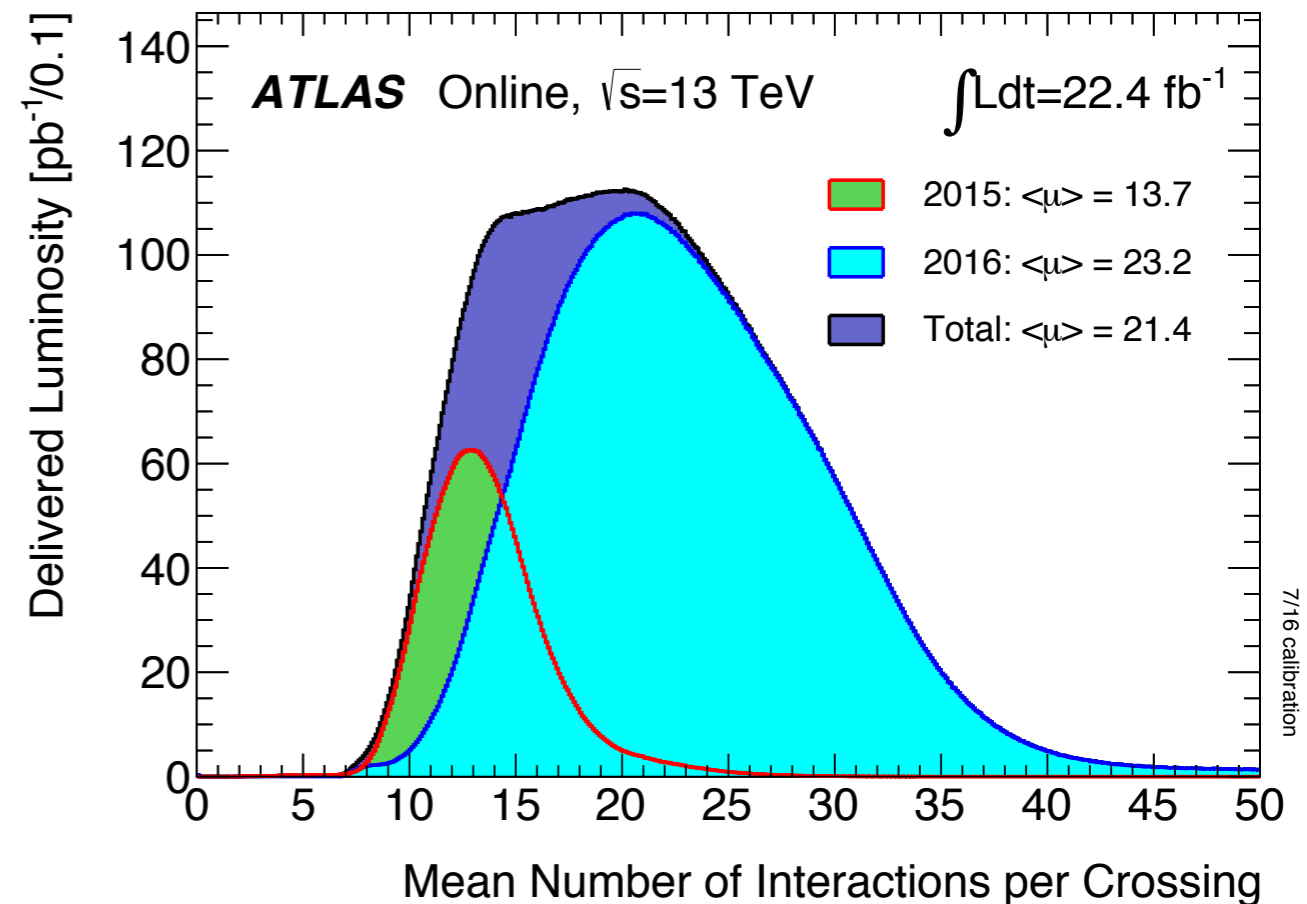
CMS Peak Luminosity Per Day, pp, 2016, $\sqrt{s} = 13$ TeV

Data included from 2016-04-22 22:48 to 2016-08-19 23:50 UTC

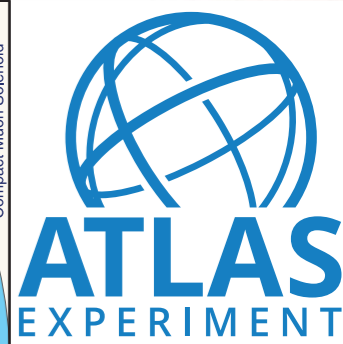


$$= 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

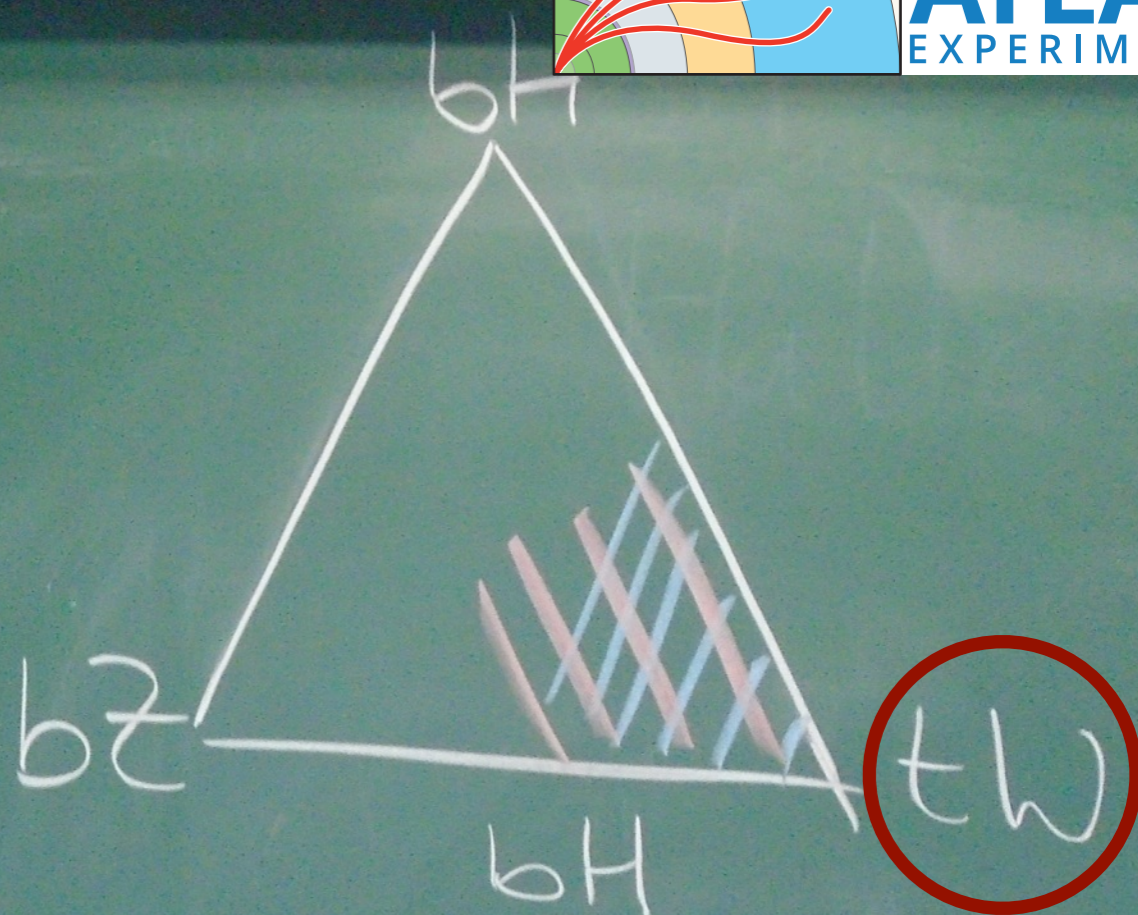
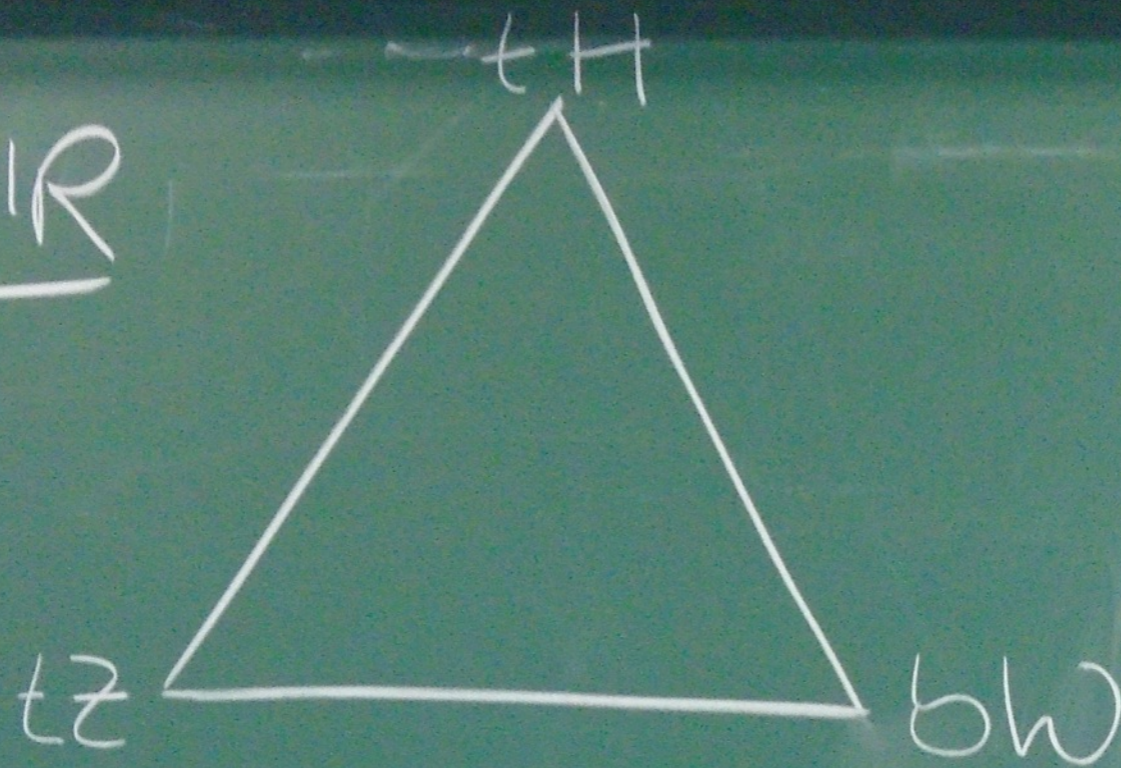
- Record in instantaneous luminosity !
- Comes with higher pile-up
- Results in this talk based on 2015 data



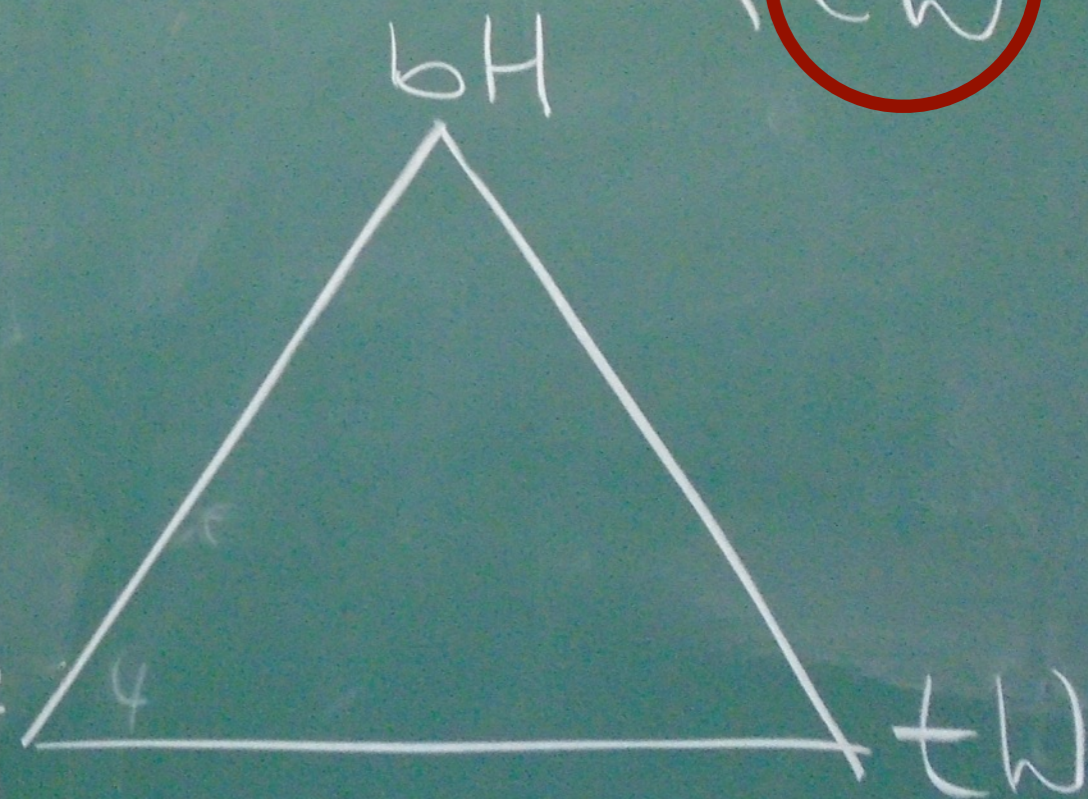
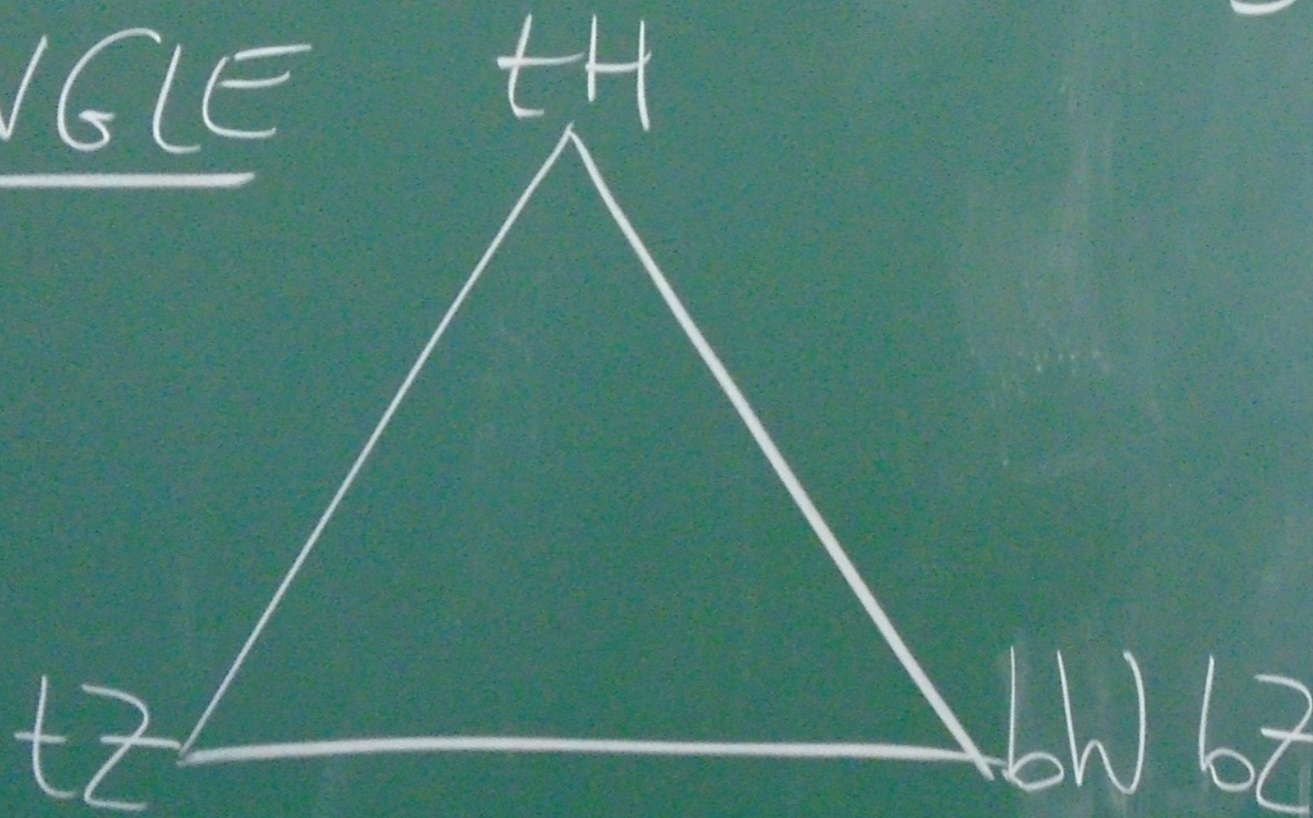
Same-Sign Leptons



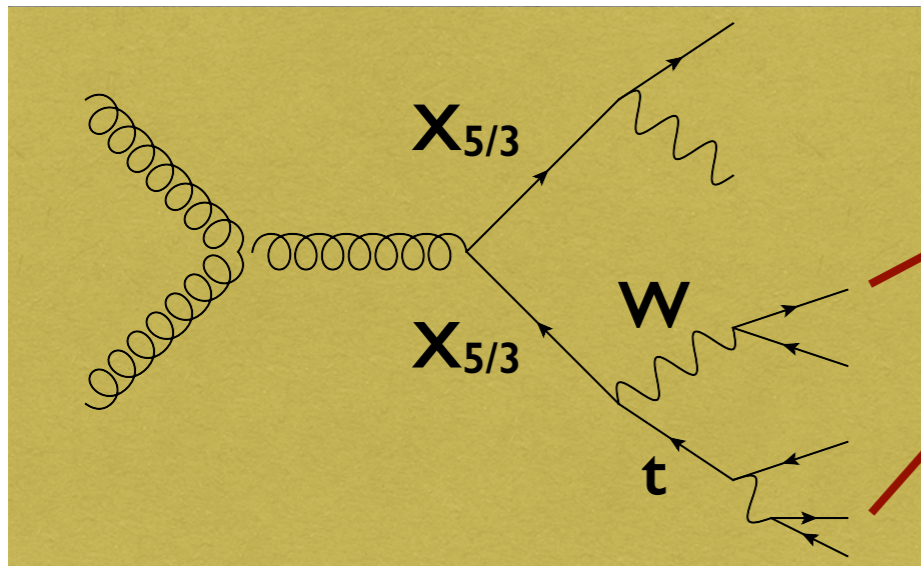
PAIR



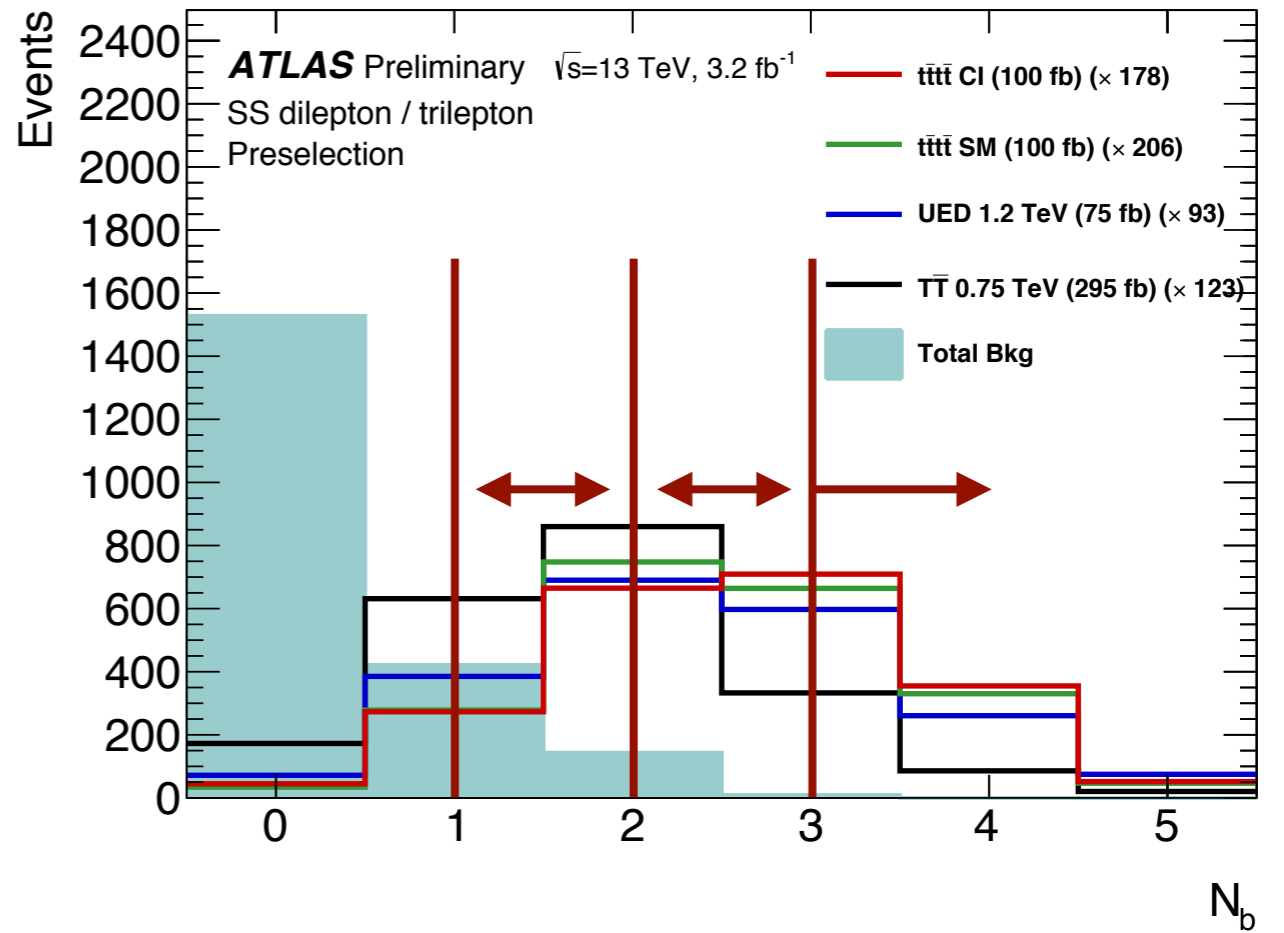
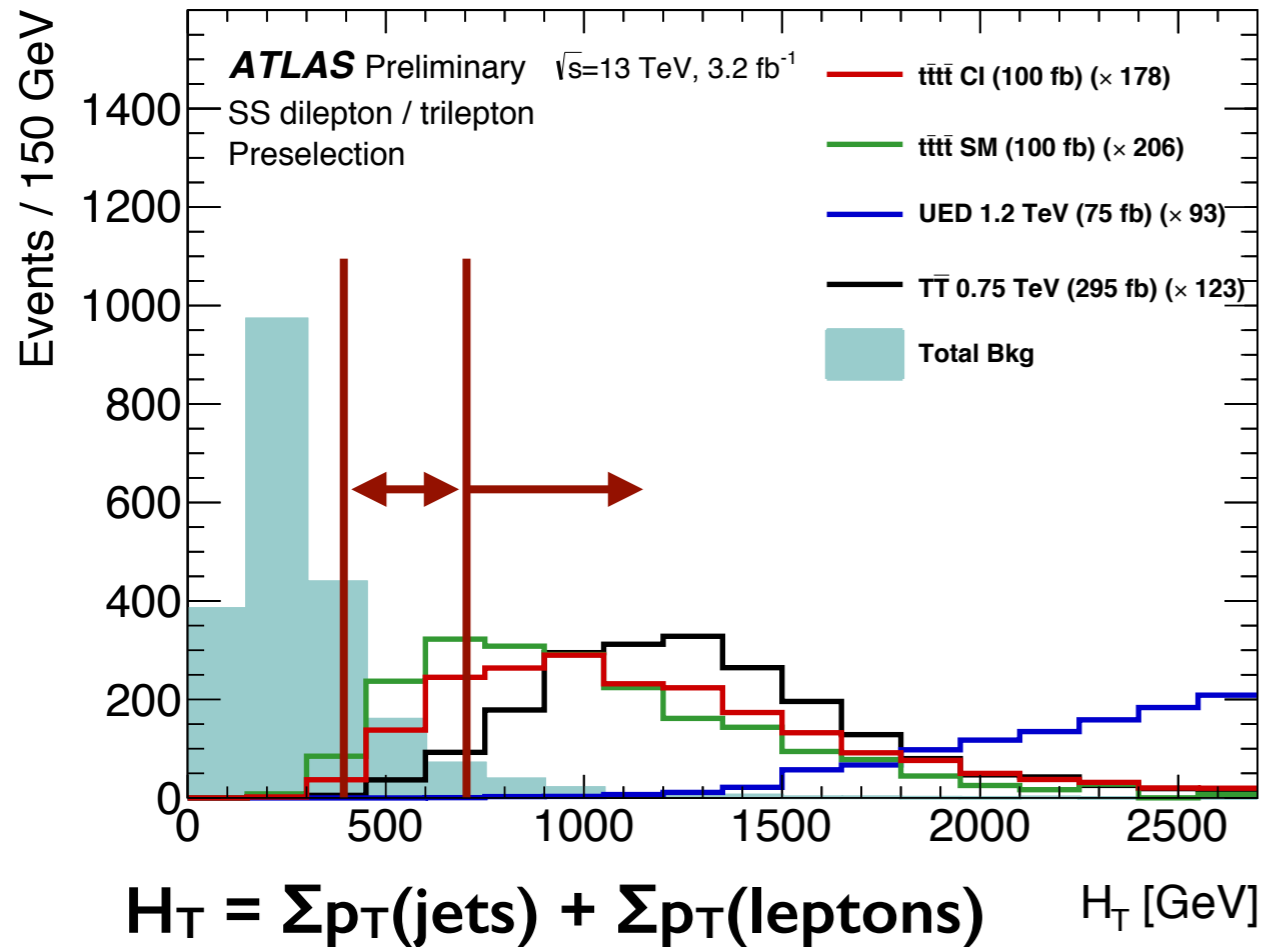
SINGLE



Same-Sign Leptons



- $e^\pm e^\pm + \mu^\pm \mu^\pm + e^\pm \mu^\pm + \text{trilepton}$
 - J/ψ and Z vetos
 - high : H_T & b-tag multiplicity & MET
 - categorize and count !
- (same 8 categories as Run-I)



Same-Sign Leptons

Main Backgrounds

$t\bar{t} + W/Z/ \dots$

- from MC

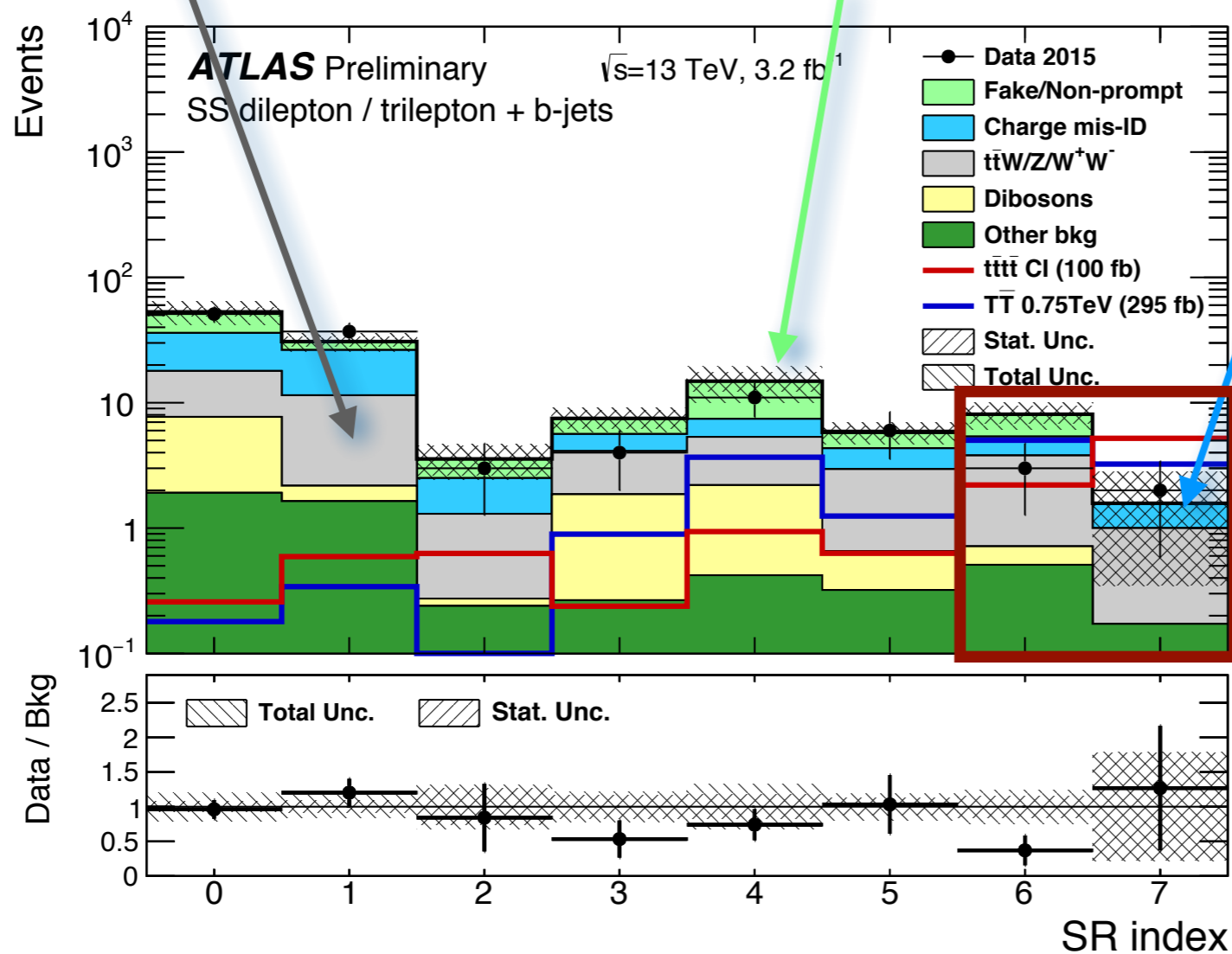
$t\bar{t} \rightarrow \ell + b\bar{b} + X$

- fake leptons
- from matrix method
- 54% systematics

$t\bar{t} \rightarrow \ell^+ \ell^- + b\bar{b} + X$

- charge mis-ID (only e^\pm)
- from $Z \rightarrow e^+e^-$
- 25% systematics
- trident electrons :
 - charge mis-ID
 - fake leptons from γ conversions

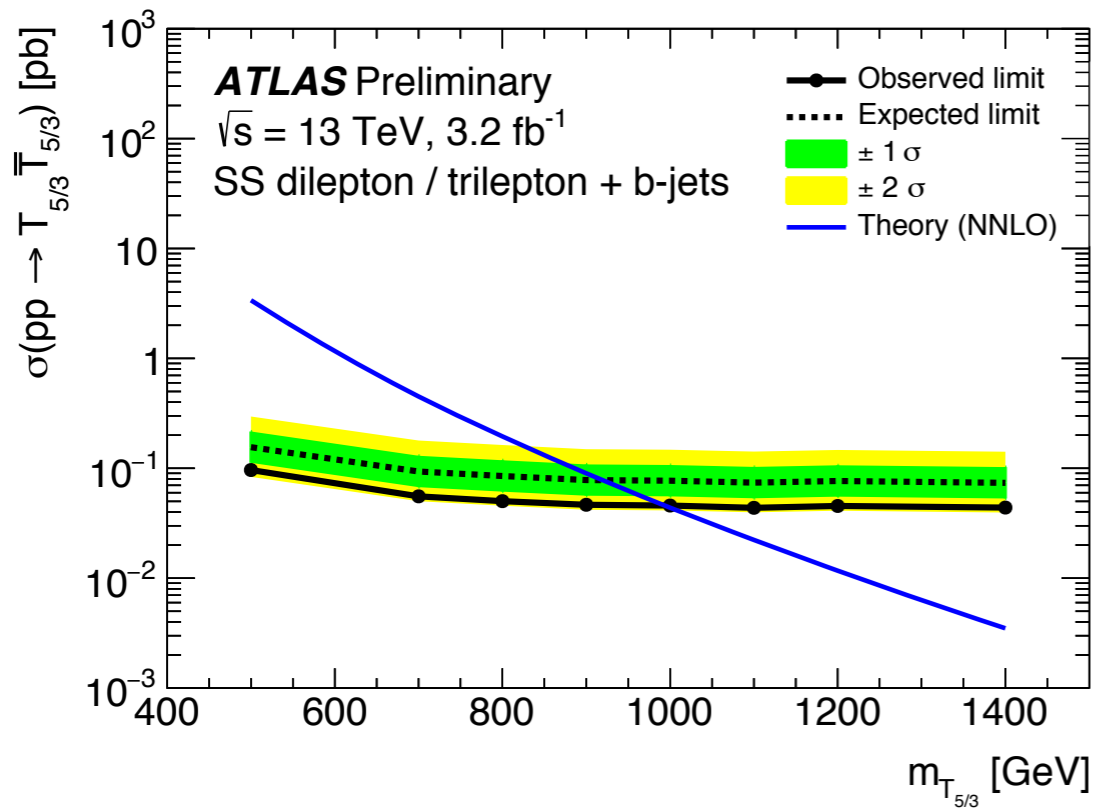
→ fake lepton subtraction to avoid double-counting



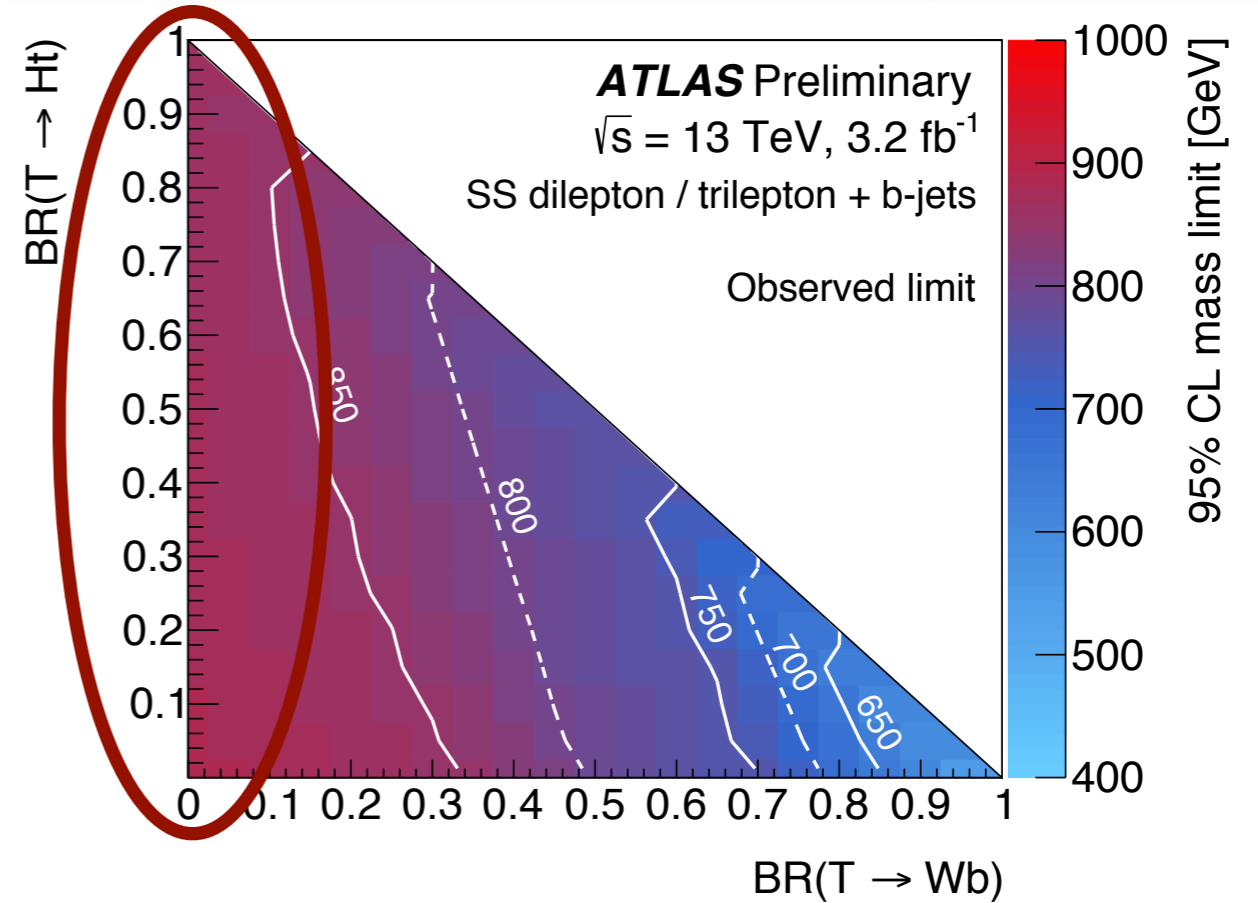
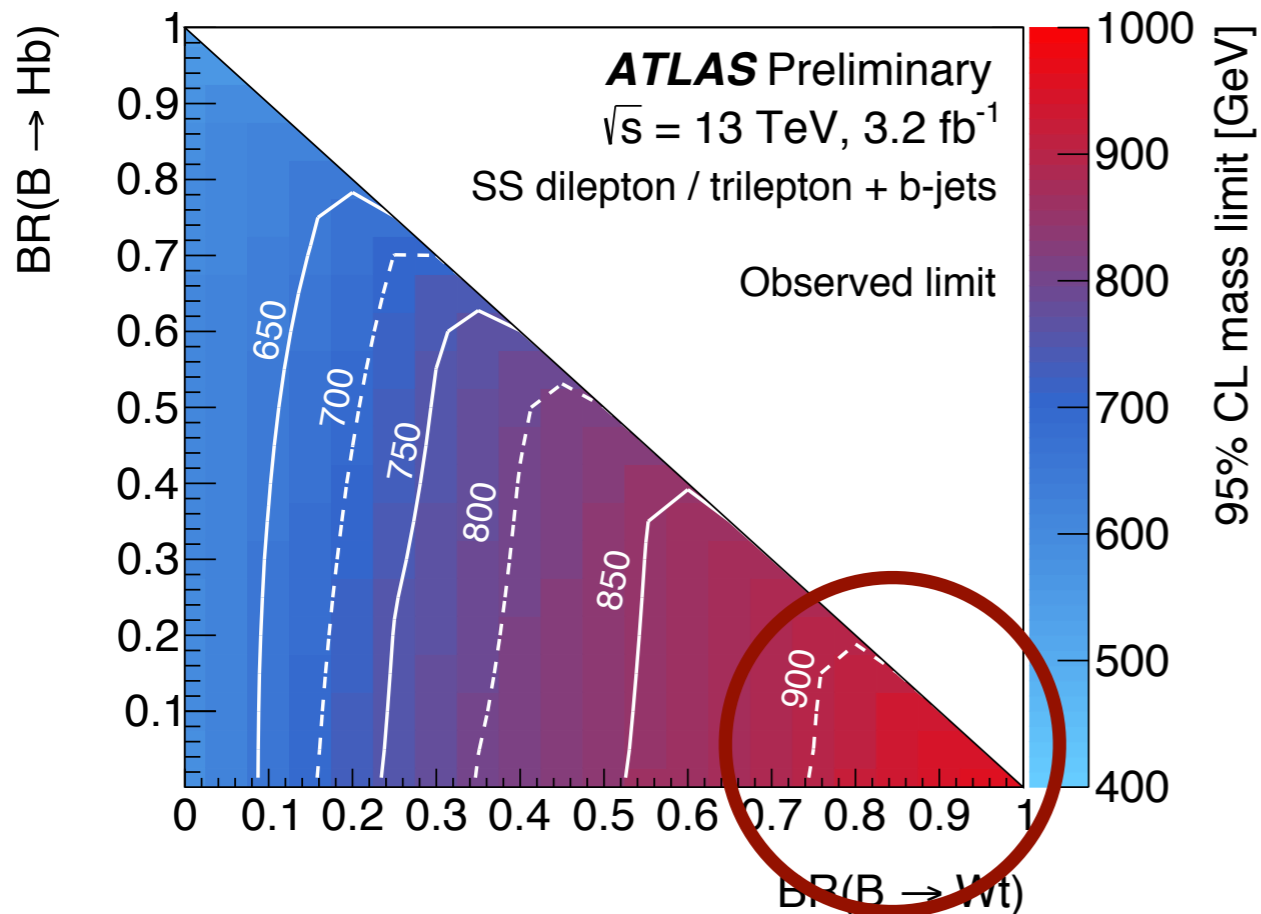
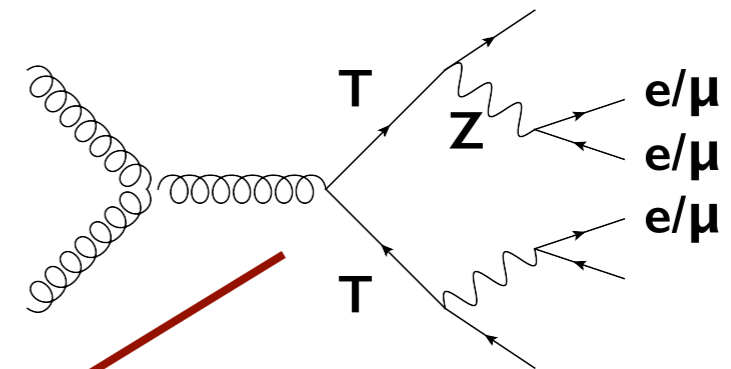
Run-1 excess not reproduced



Same-Sign Leptons

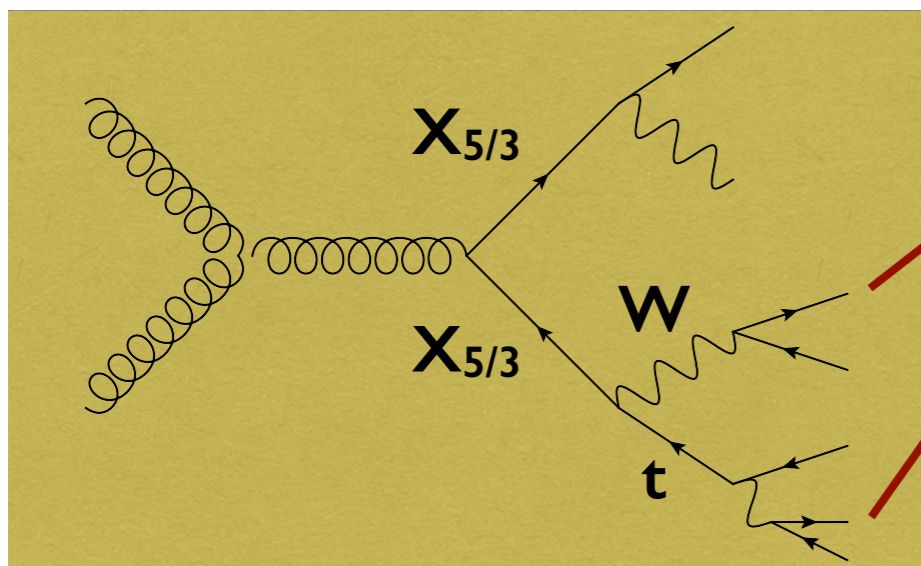


- $m(X_{5/3}) > 0.99 \text{ TeV}$ (was 0.74 TeV @ Run-1)
- $m(B|\text{singlet}) > 0.83 \text{ TeV}$ (was 0.69 TeV)
- $m(T|\text{singlet}) > 0.78 \text{ TeV}$ (was 0.66 TeV)
- sensitivity to T via $H \rightarrow WW^*$ or $Z \rightarrow l^+l^-$



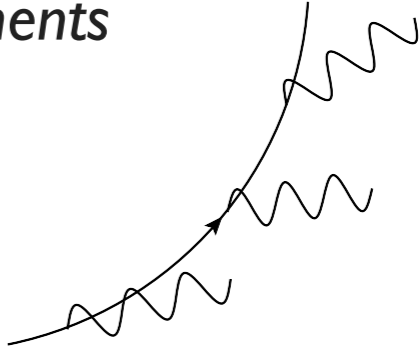
Same-Sign Leptons & l+jets

CMS PAS B2G-15-006 (12/15)



- $e^\pm e^\pm + \mu^\pm \mu^\pm + e^\pm \mu^\pm$
- J/ ψ and Z vetos
- high : H_T & $p_T(\text{lep})$ & $\#(\text{jets+leptons})$
- no b-tag requirement
- count in lepton flavor categories !

- e^\pm charge mis-ID suppressed by comparing up to 3 charge measurements
- standard track reconstruction (Kalman filter)
- Gaussian sum filter \rightarrow improve bremsstrahlung modeling
- rel. position of cluster and track (for $p_T < 100$ GeV)



prompt same-sign

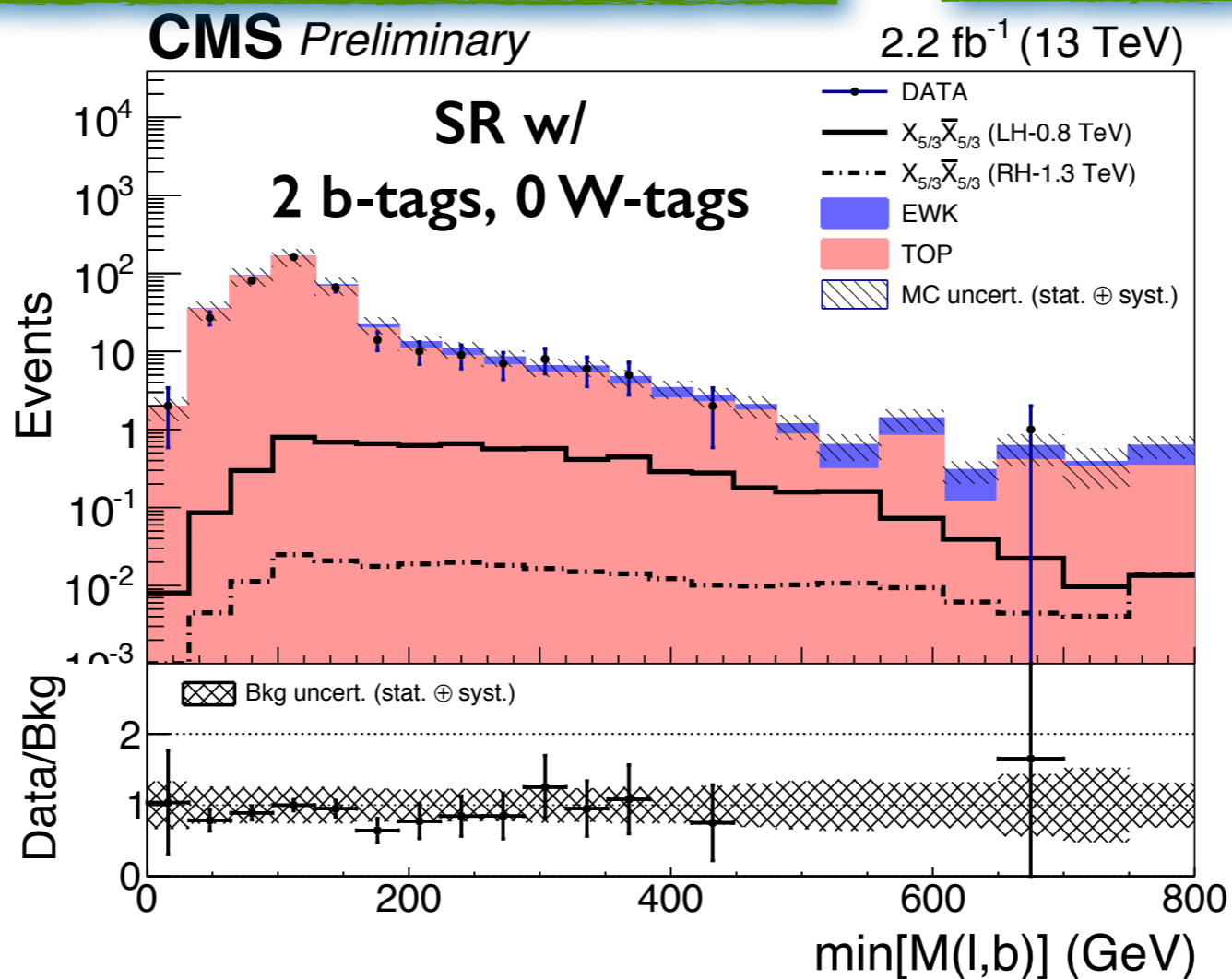
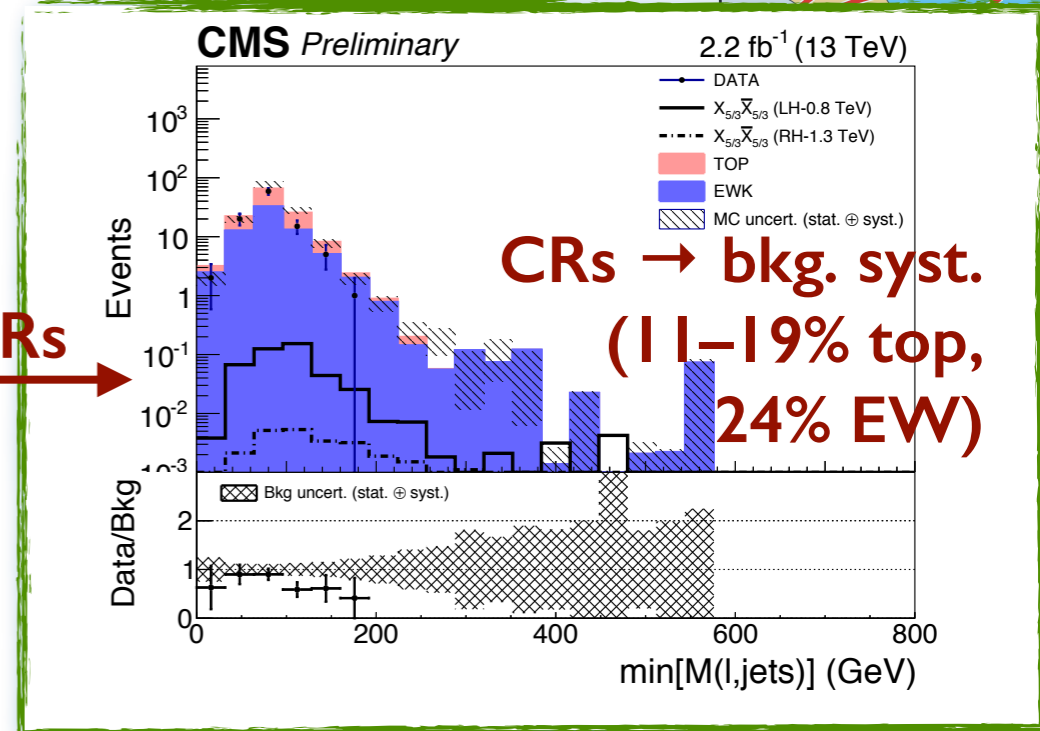
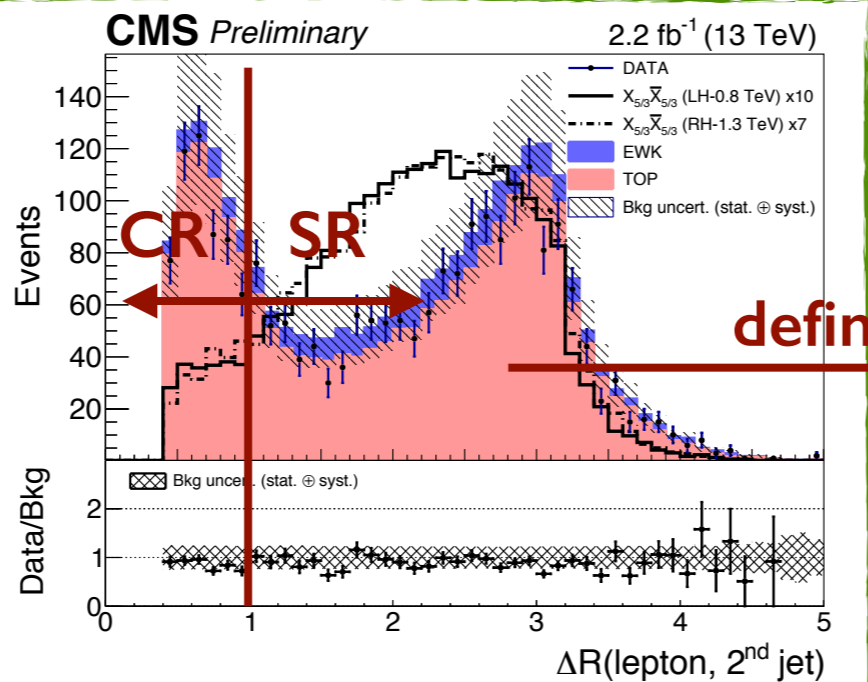
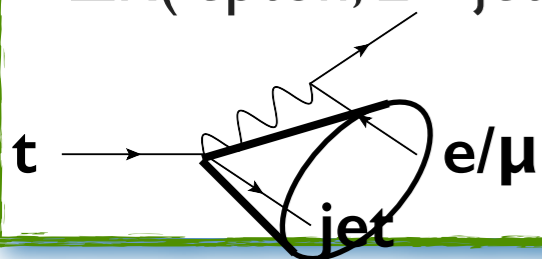
Channel	PSS MC	NonPrompt	ChargeMisID	Total Background	800 GeV $X_{5/3}$	Observed
Di-electron	2.41 ± 0.29	2.16 ± 1.91	1.90 ± 0.60	6.47 ± 2.02	4.38	7
Electron-Muon	2.98 ± 0.36	5.20 ± 3.21	0.54 ± 0.18	8.72 ± 3.24	9.14	3
Di-muon	0.70 ± 0.12	2.09 ± 1.69	0.00 ± 0.00	2.80 ± 1.70	3.55	1
All	6.09 ± 0.67	9.45 ± 5.49	2.44 ± 0.76	17.98 ± 5.58	17.06	11

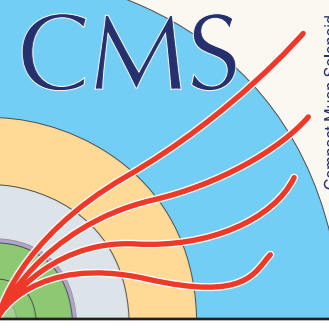
Same-Sign Leptons & l+jets

CMS PAS B2G-15-006 (12/15)

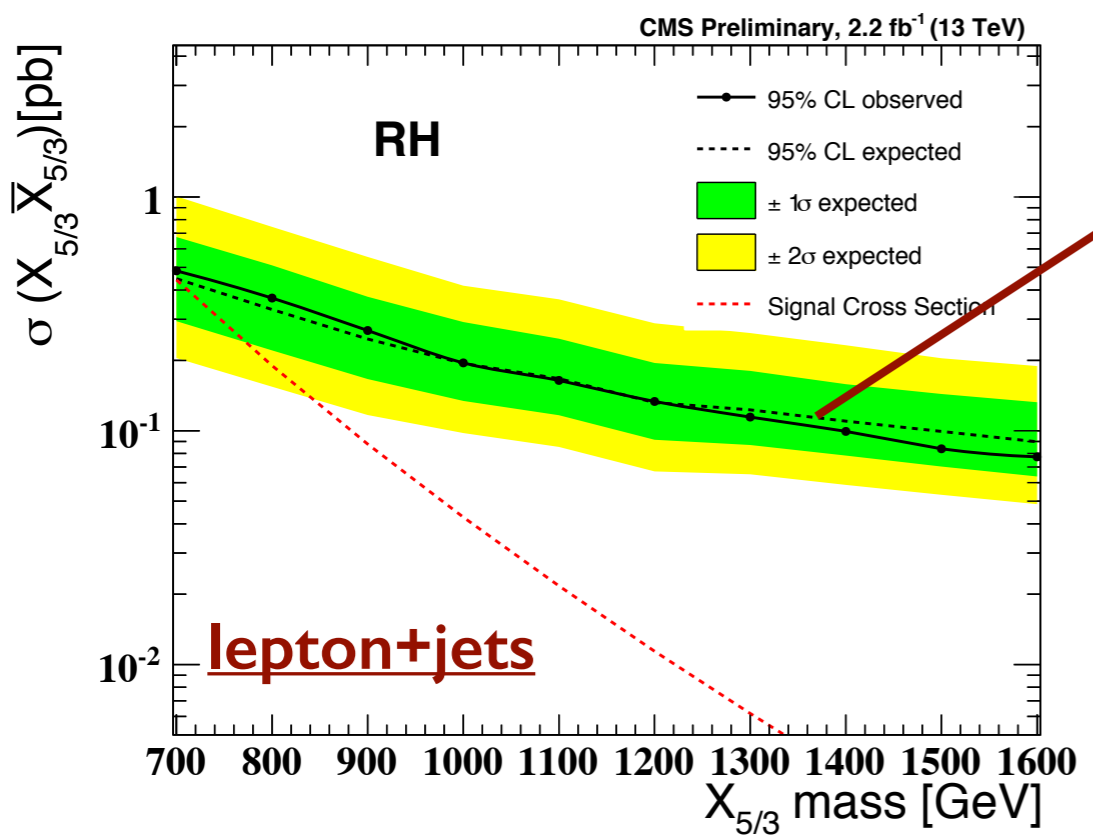
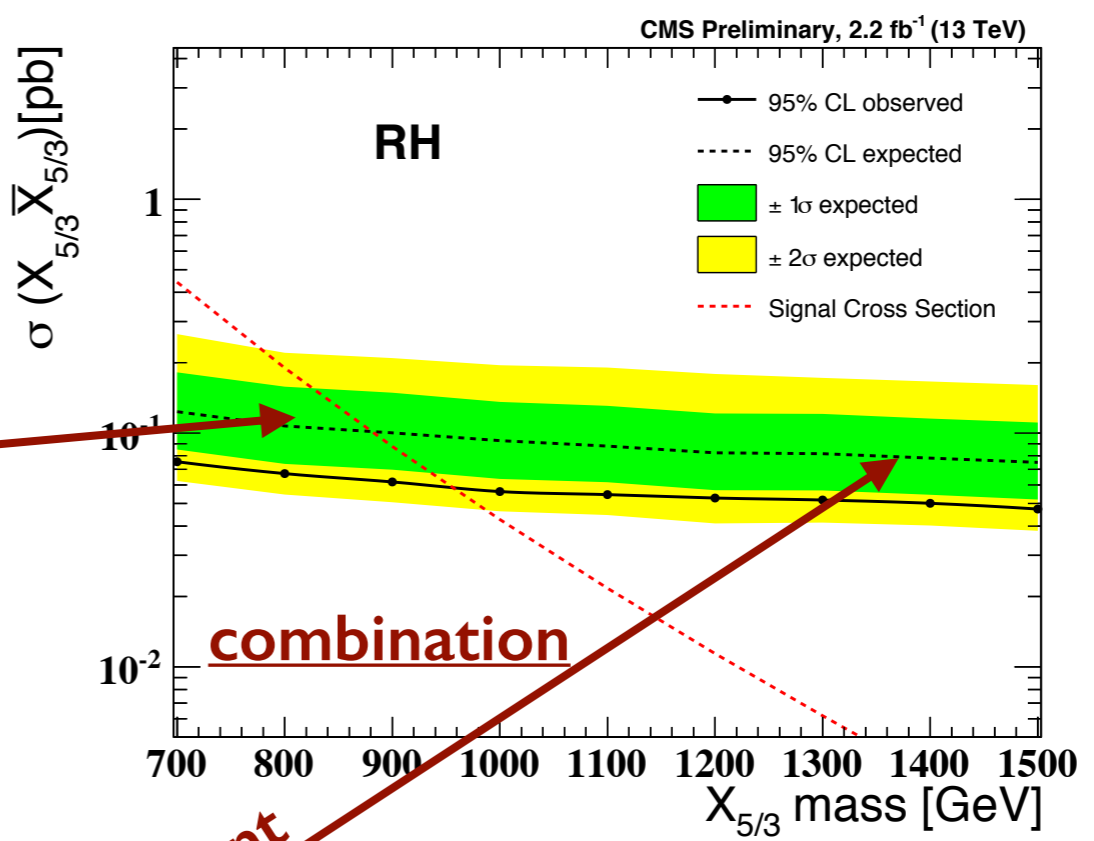
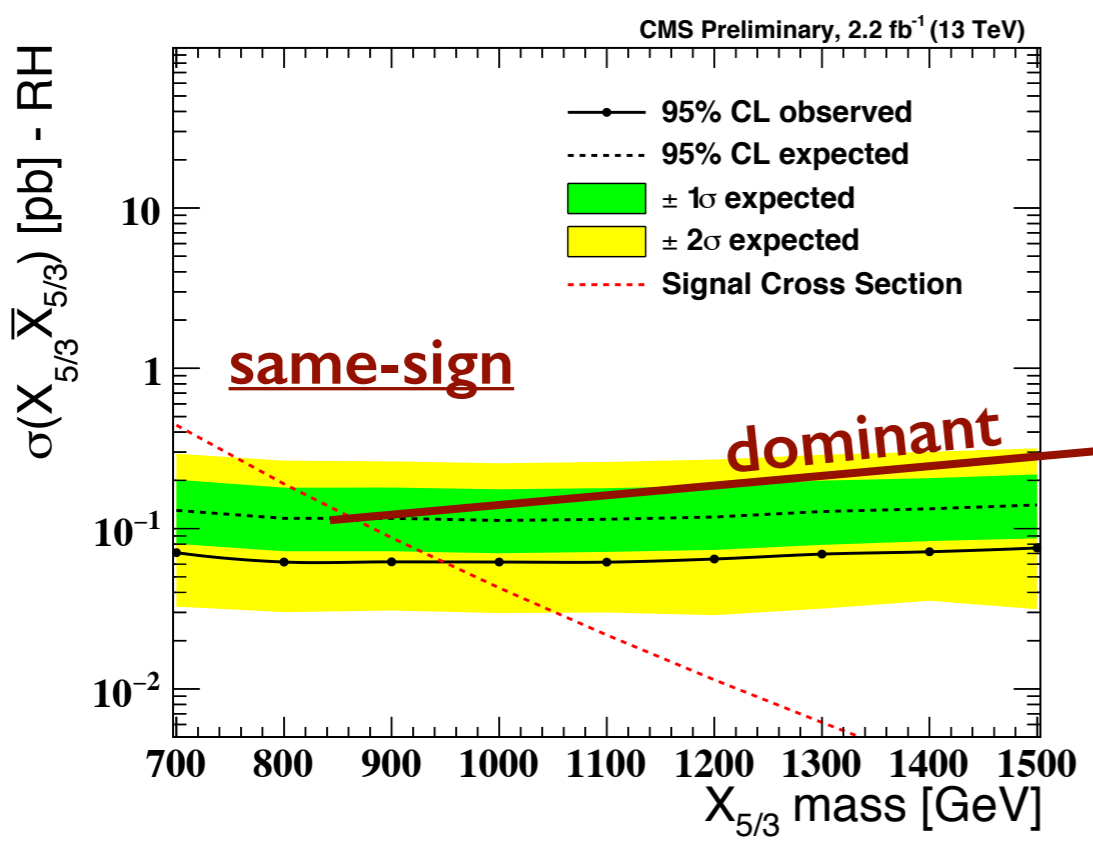
New l+jets channel

- high lepton p_T , MET, jet multiplicity & p_{T_S}
- 4 categories: #b, #W
- $\Delta R(\text{lepton}, 2^{\text{nd}} \text{ jet})$





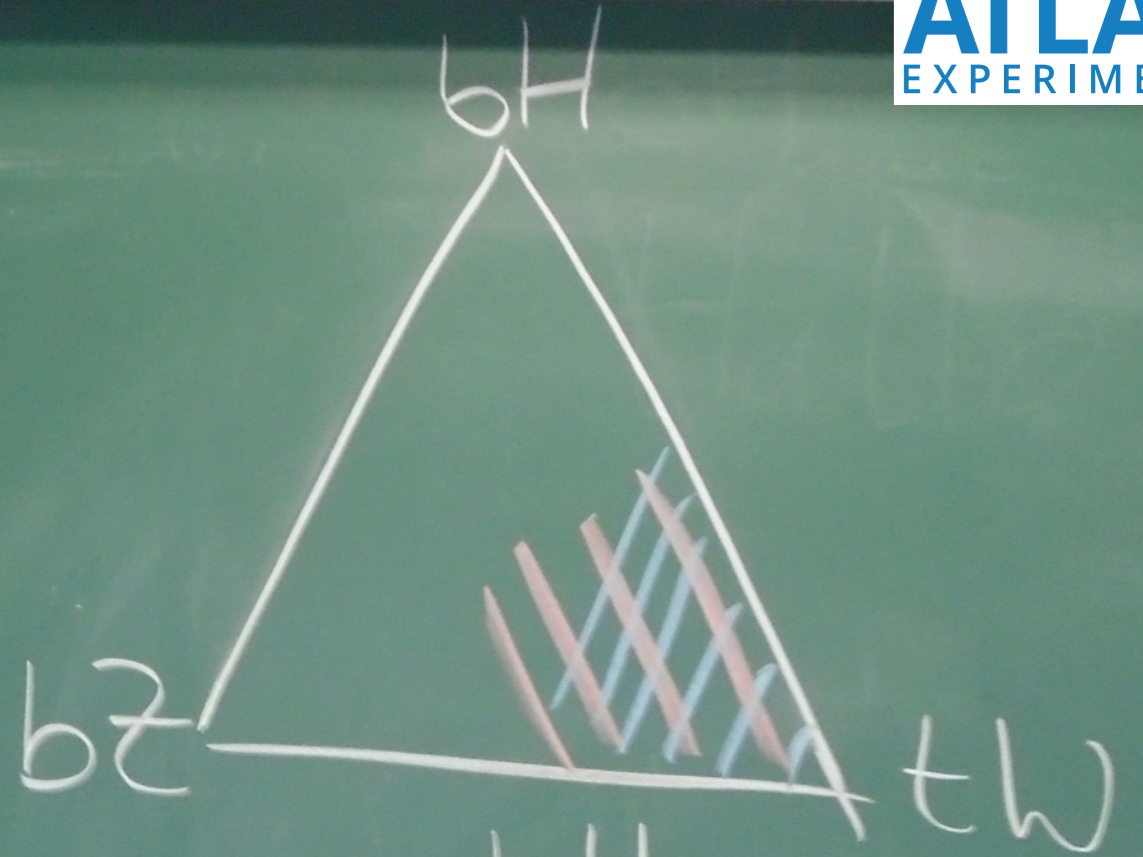
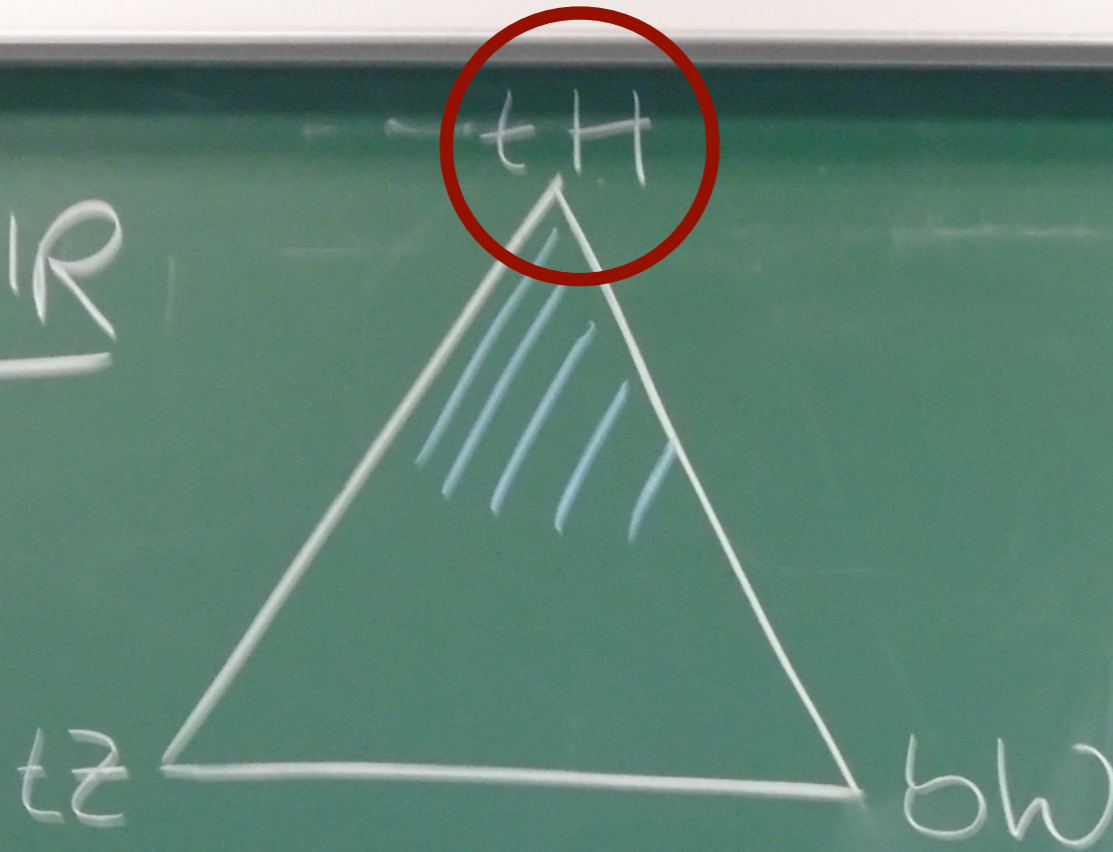
Same-Sign Leptons & l+jets



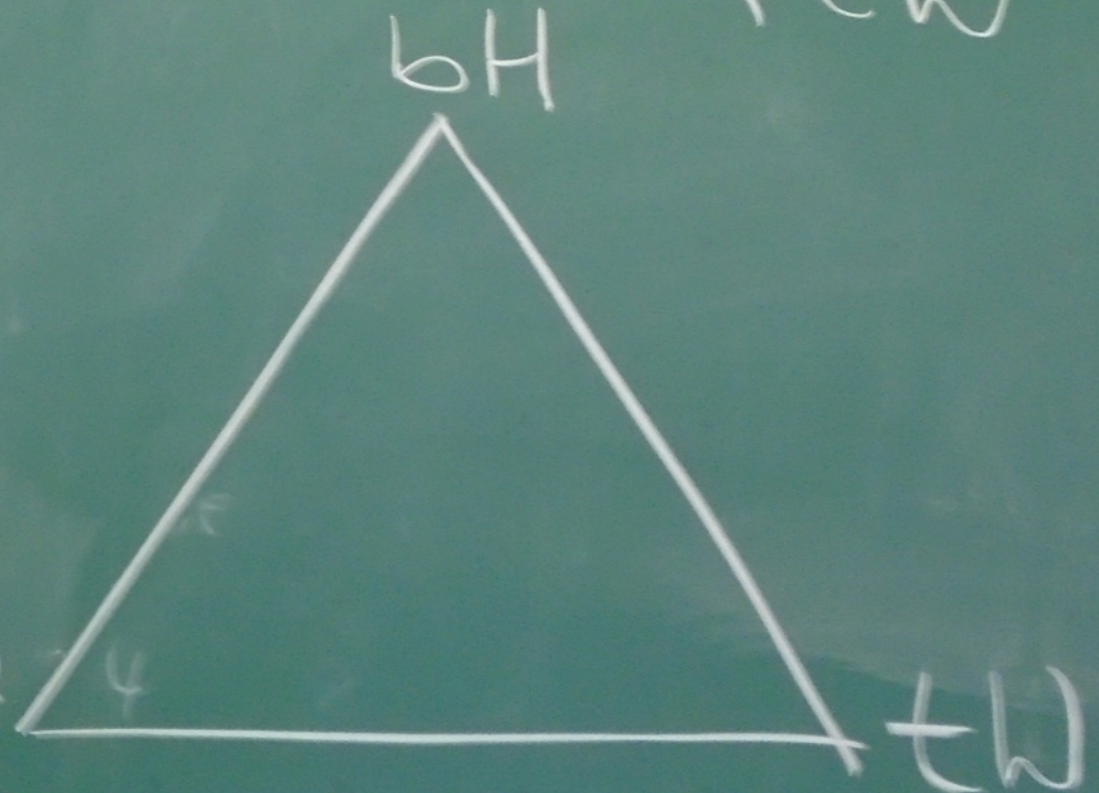
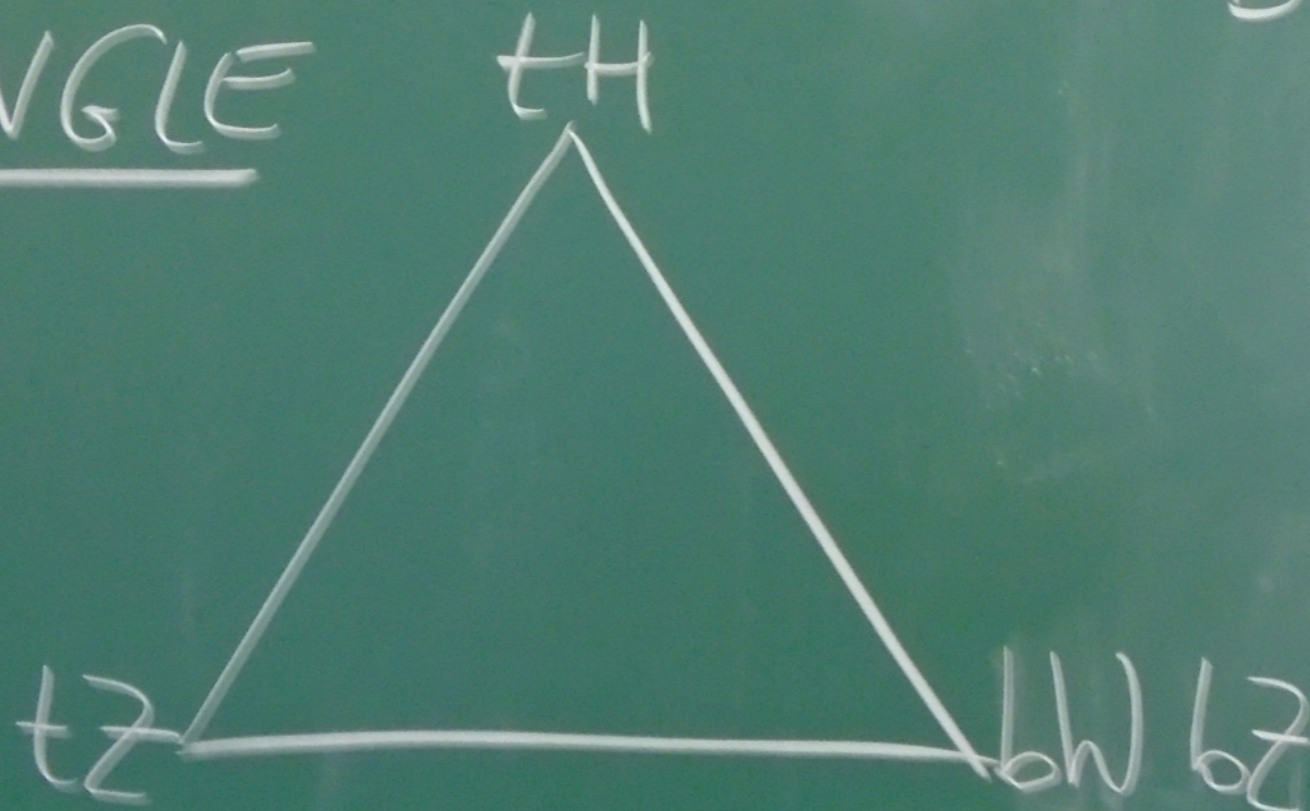
- $m(X_{5/3}|RH) > 950 \text{ GeV}$ (was 800 GeV)
- $m(X_{5/3}|LH) > 910 \text{ GeV}$ (was 800 GeV)
- ATLAS slightly more sensitive (920 vs. 900/860 GeV)
- CMS improves at high mass due to l+jets

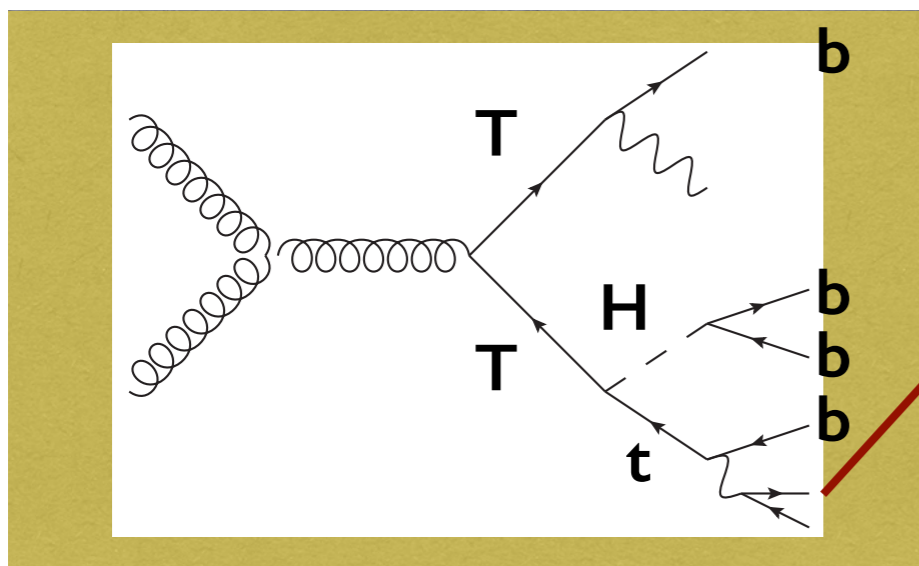
Ht+X

PAIR

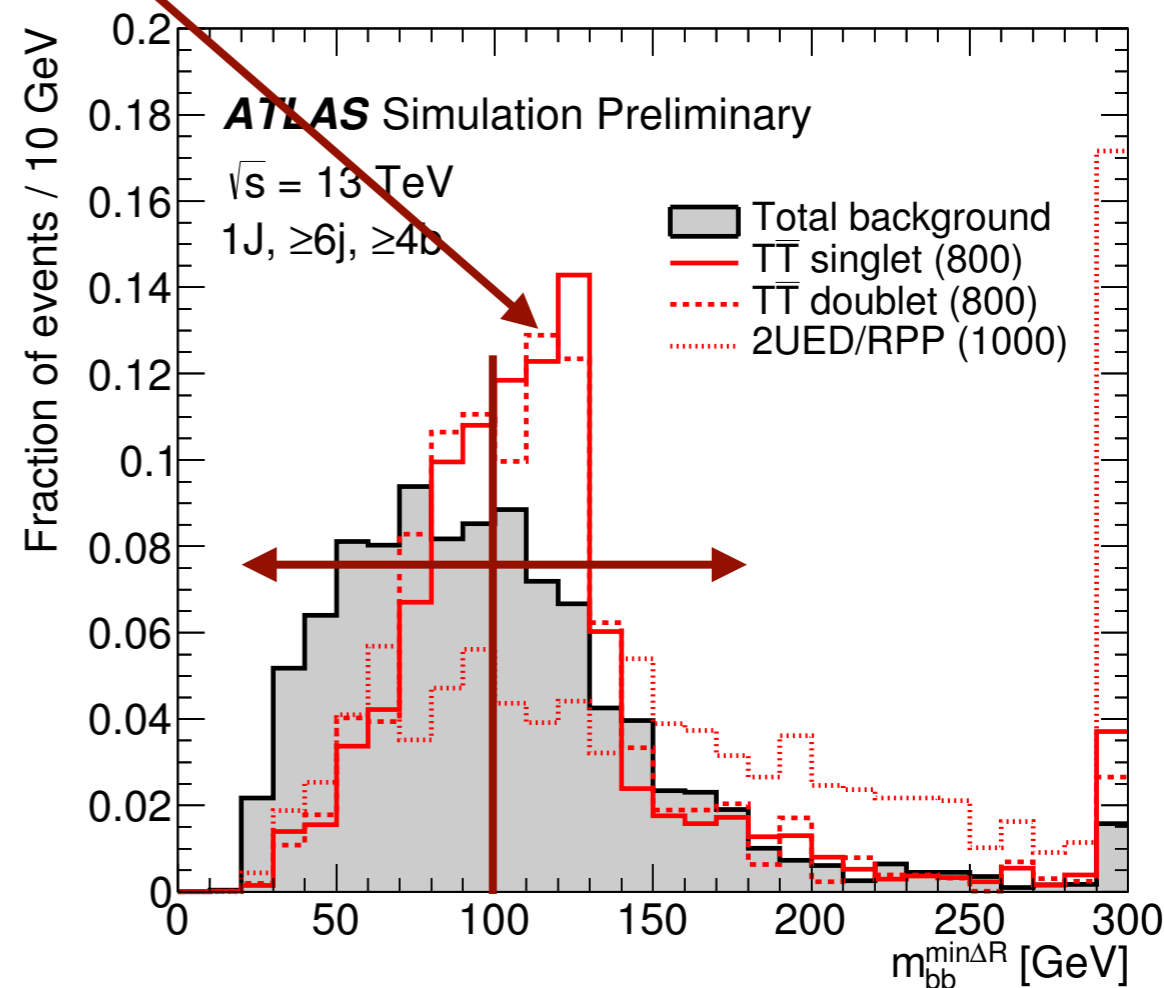
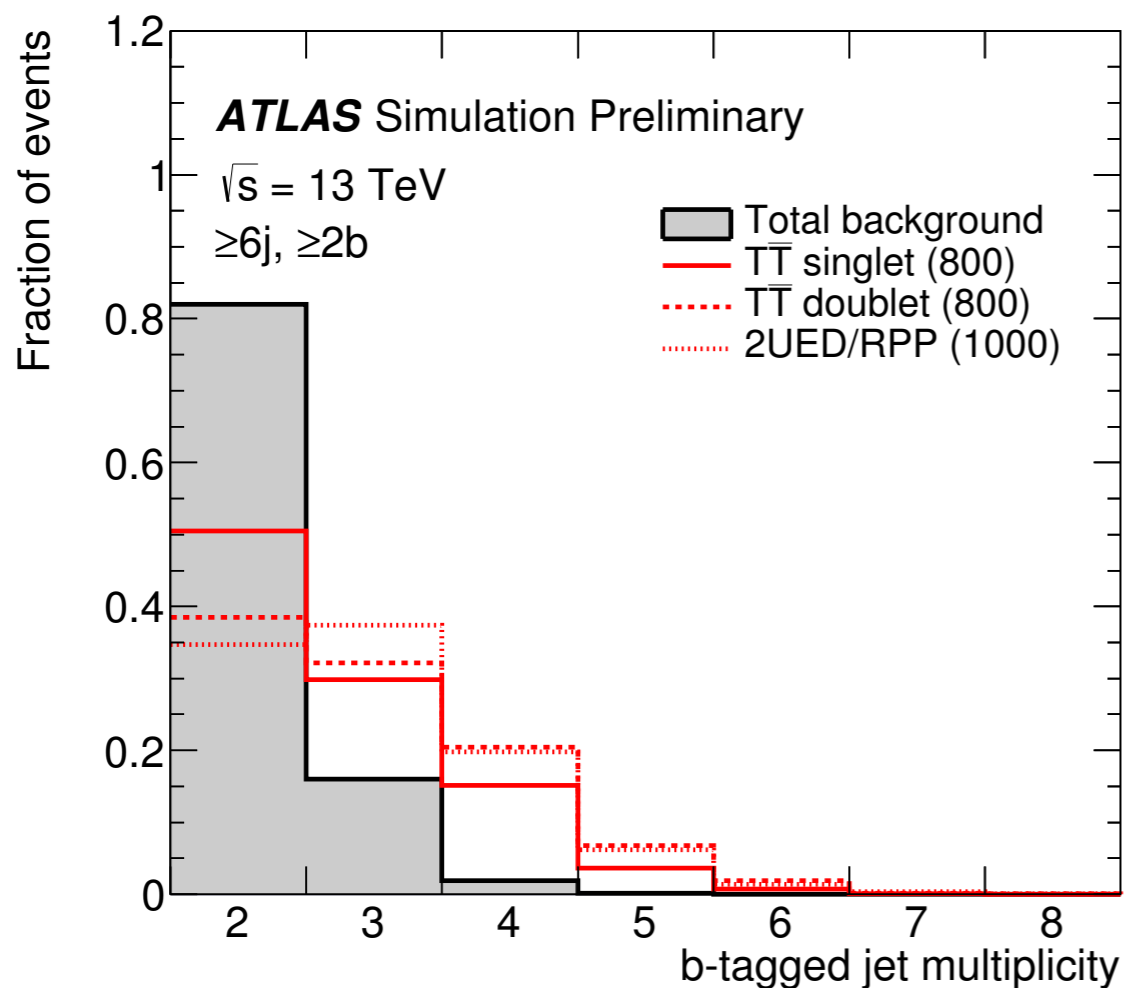


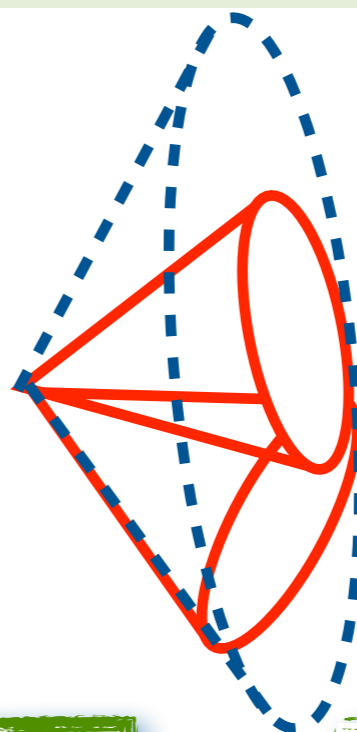
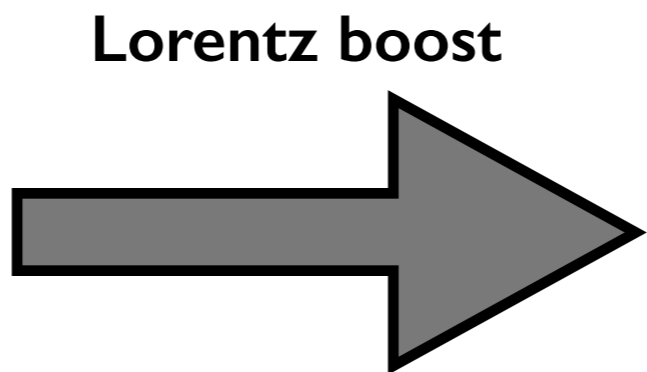
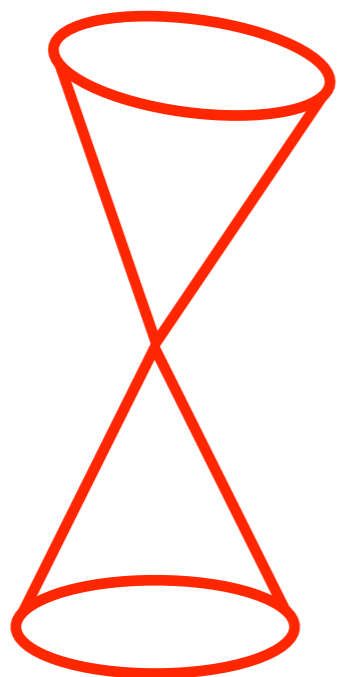
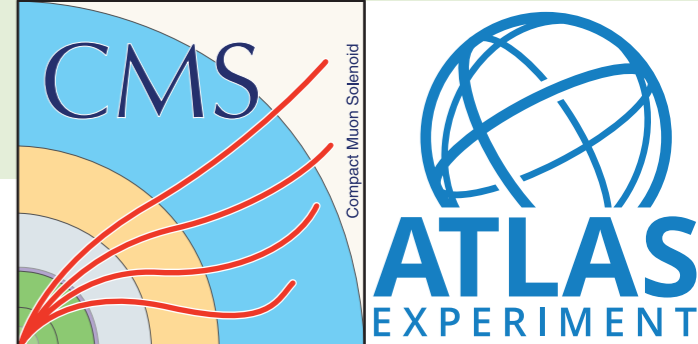
SINGLE





- Exactly one lepton
- Many b-jets, many jets, some MET
- Dominant background : top+b/c+X
- Categorize in #b, #fat-jets (next slide), m_{bb} of closest b-jets (from Higgs)





large-R jet

Excellent discriminant

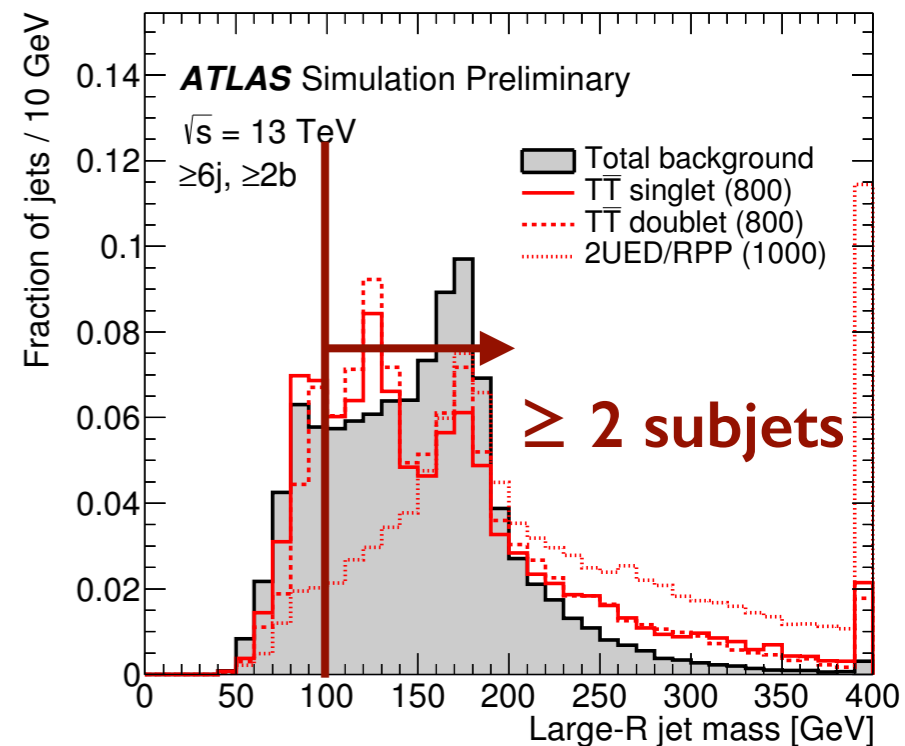
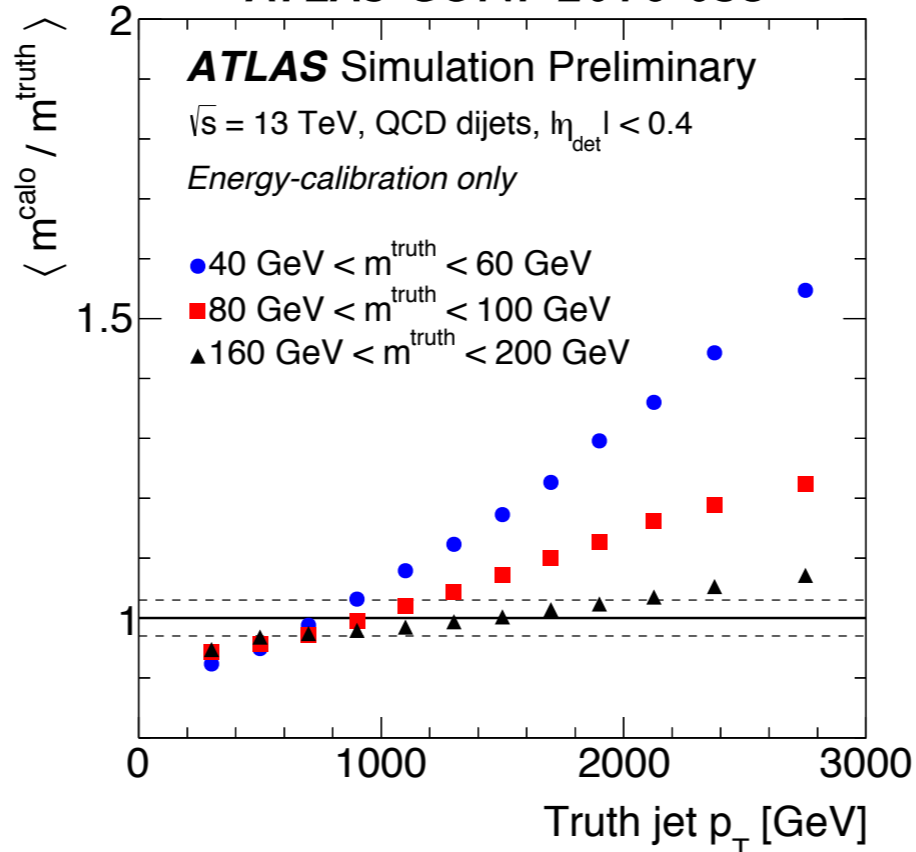
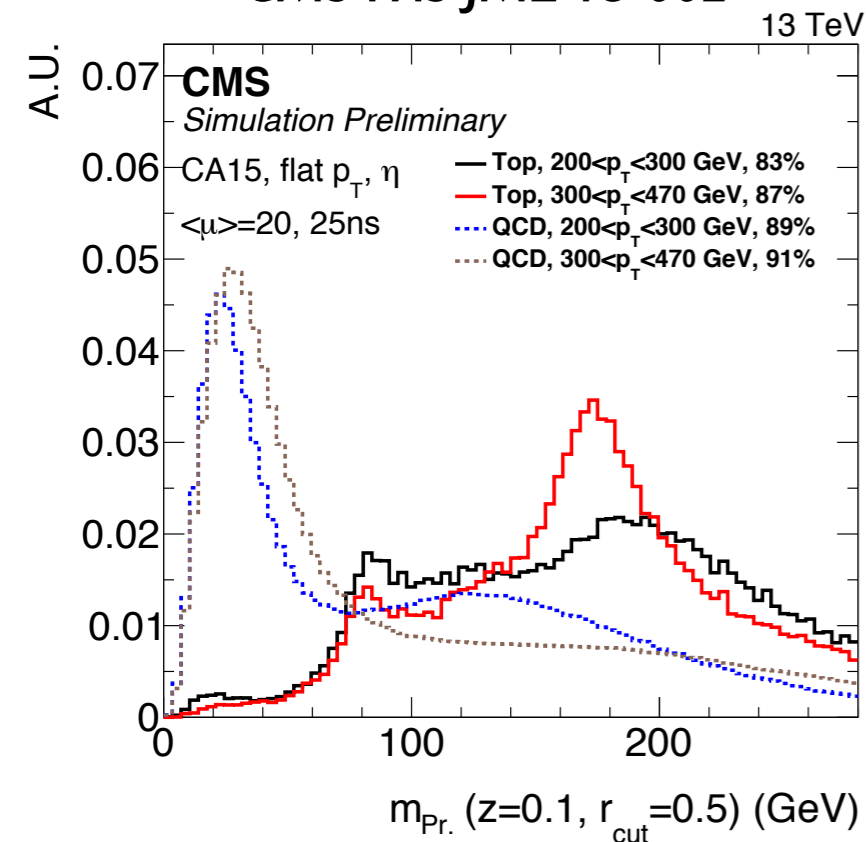
Needs calibration

Or : recluster small-R jets

CMS PAS JME-15-002

ATLAS-CONF-2016-035

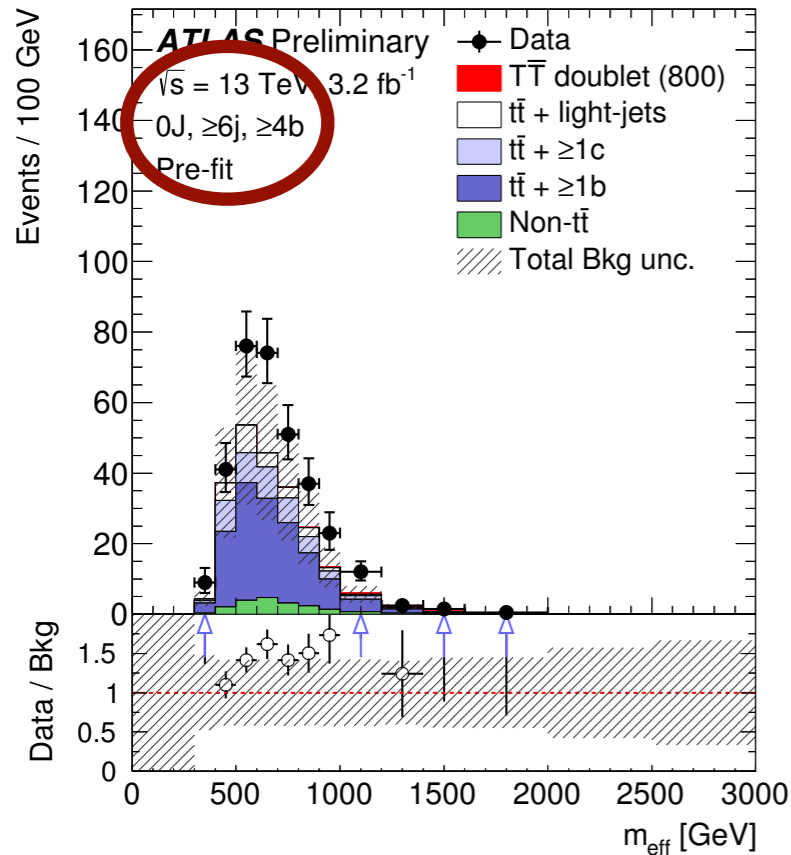
ATLAS-CONF-2016-013



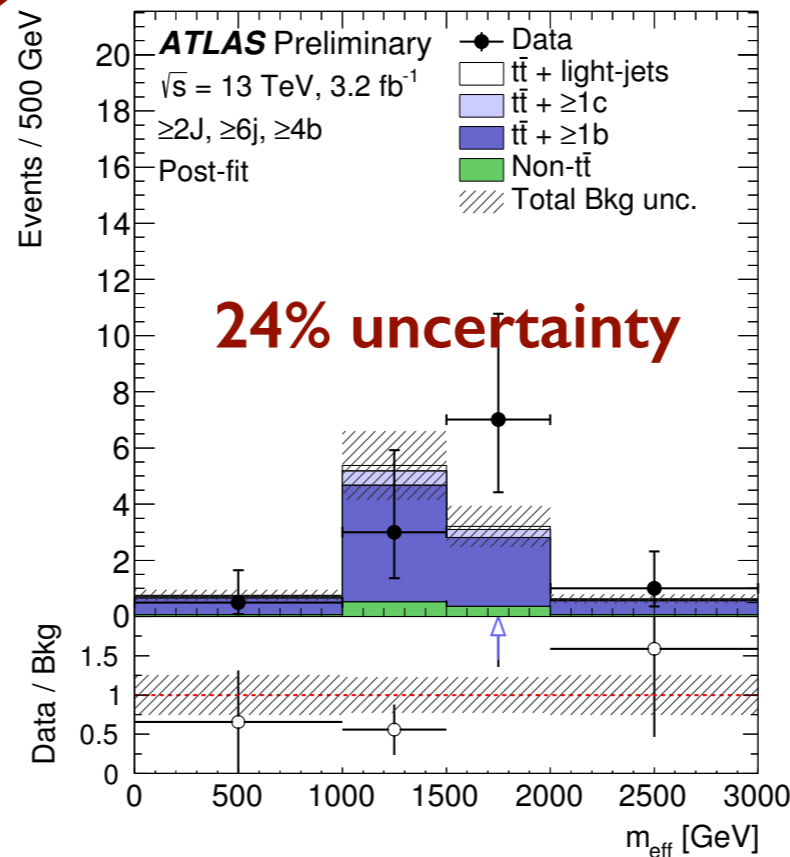
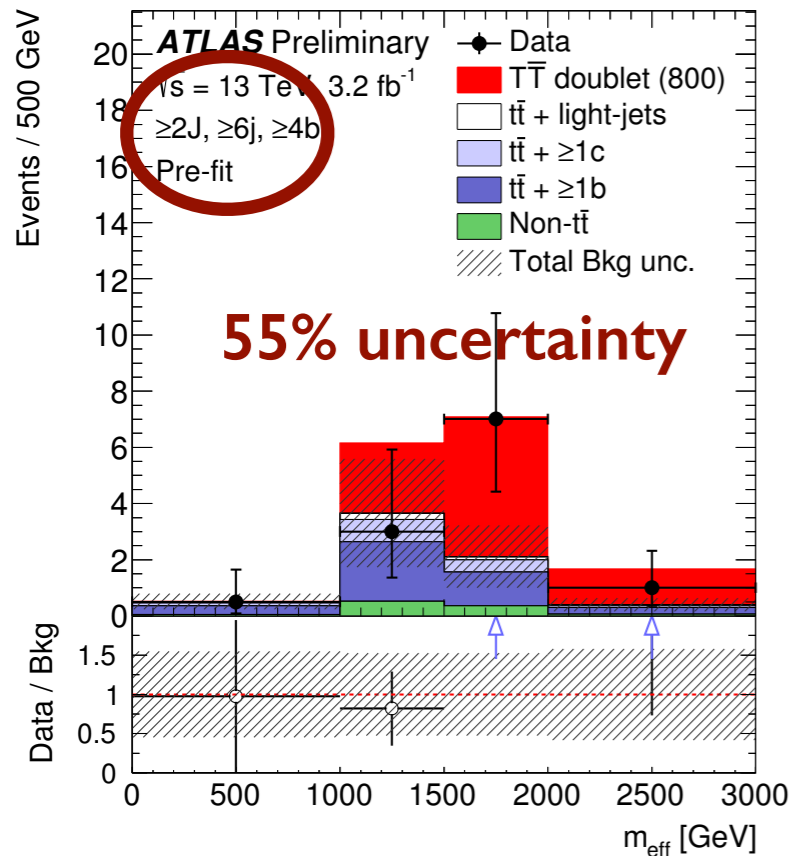
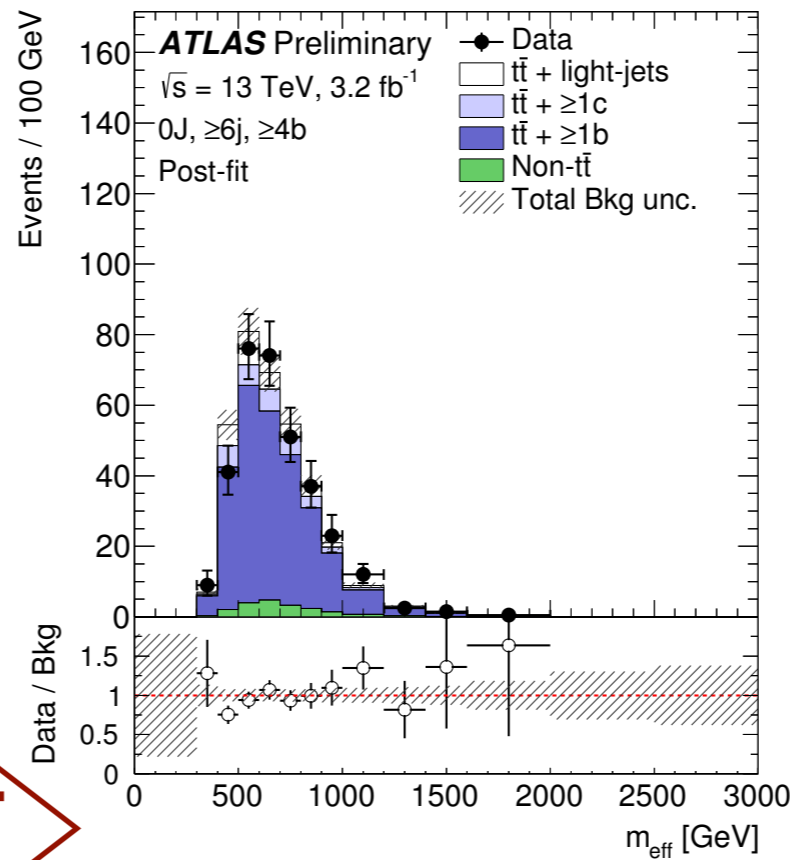
→ simple "mass tagging"

Ht+X

ATLAS-CONF-2016-013 (03/16)



FIT

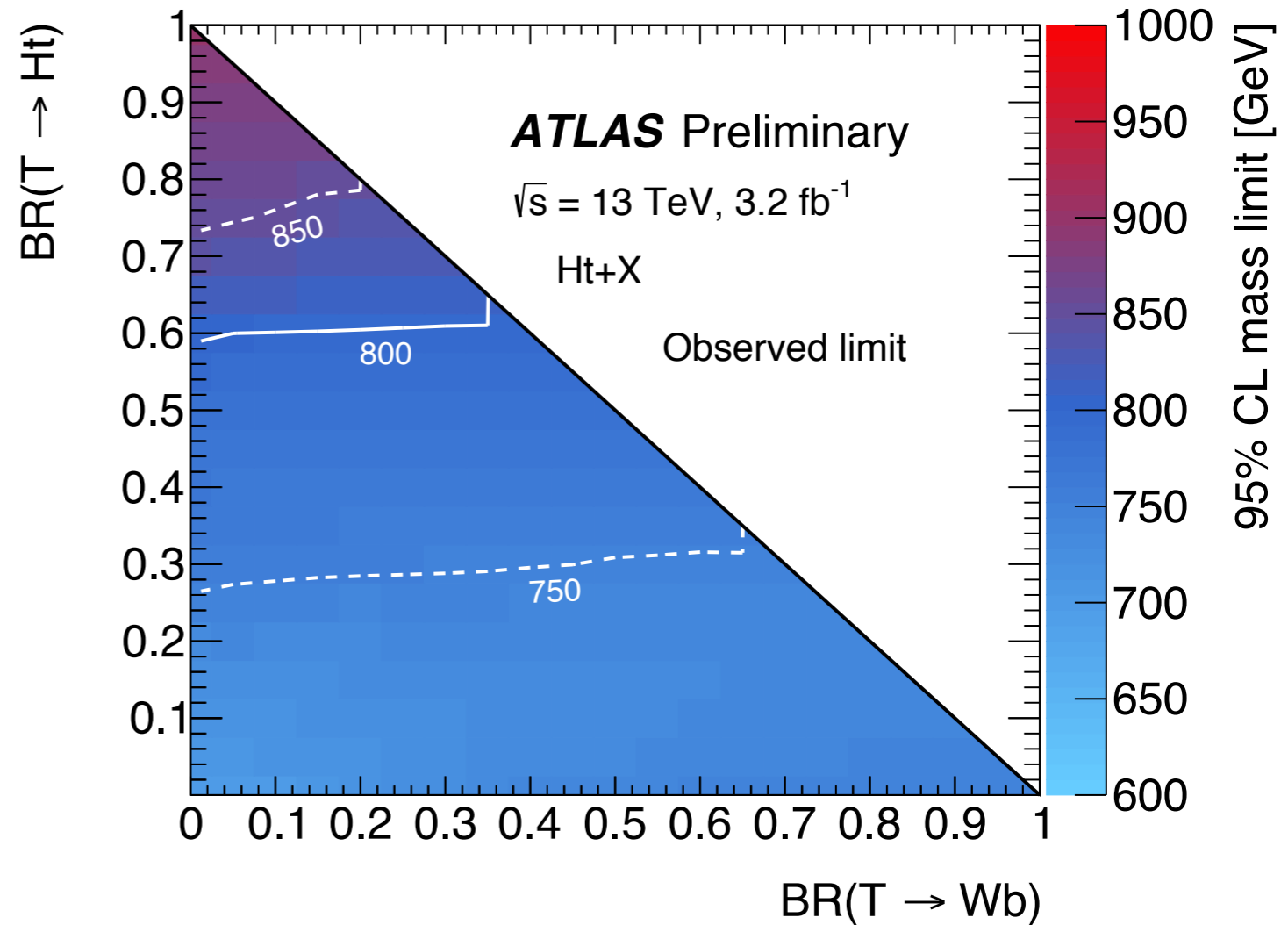
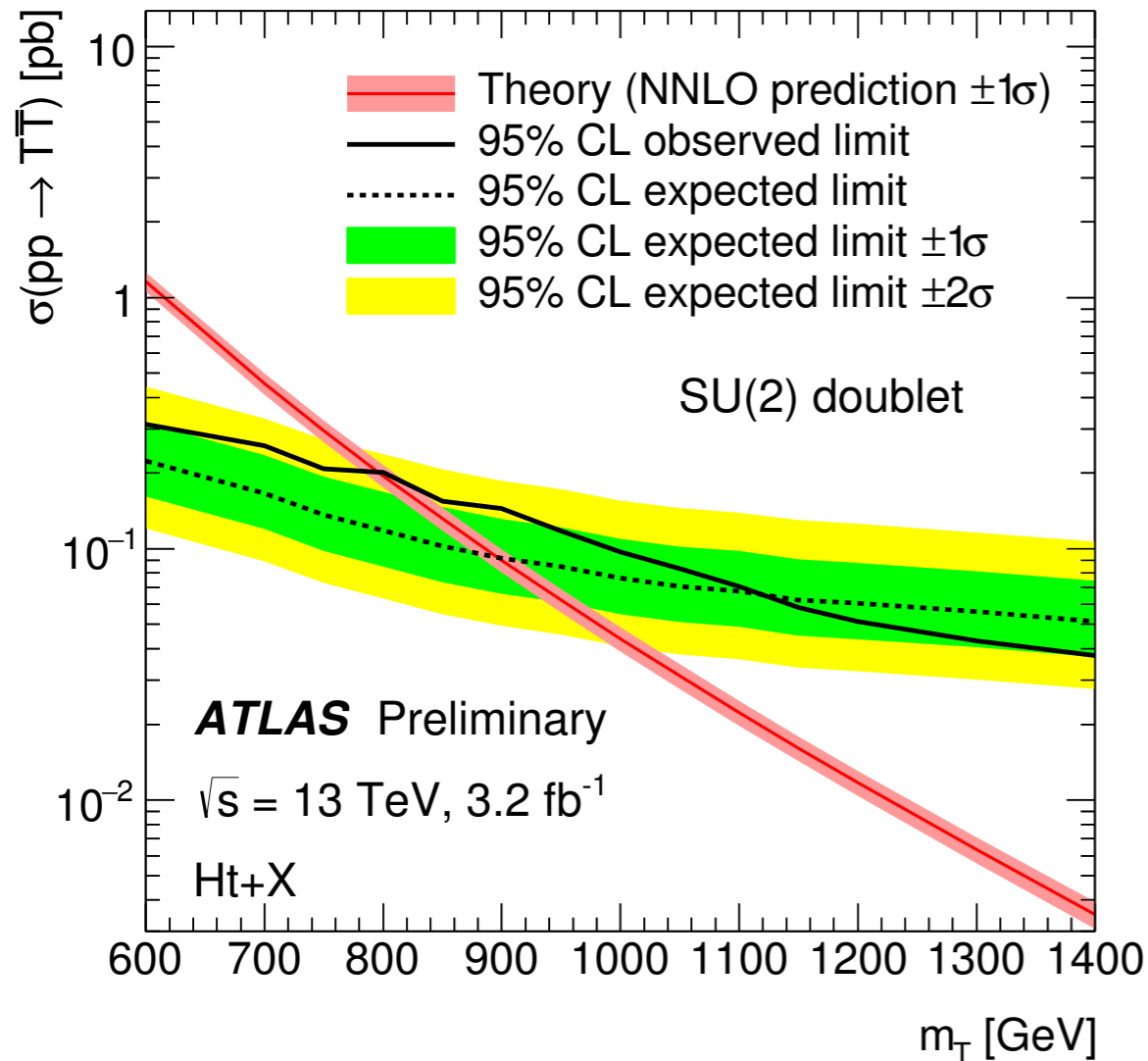


Heavy Profiling

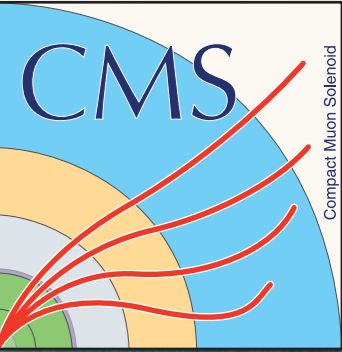
top+HF poorly known

- 11 categories fit with complex top model
 - low to high sig. purity
- profile top+LF/c/b
- *systematics:*
 - *decorrelate certain top modeling uncertainties for top+LF/c/b*
- key to controlling bkg.

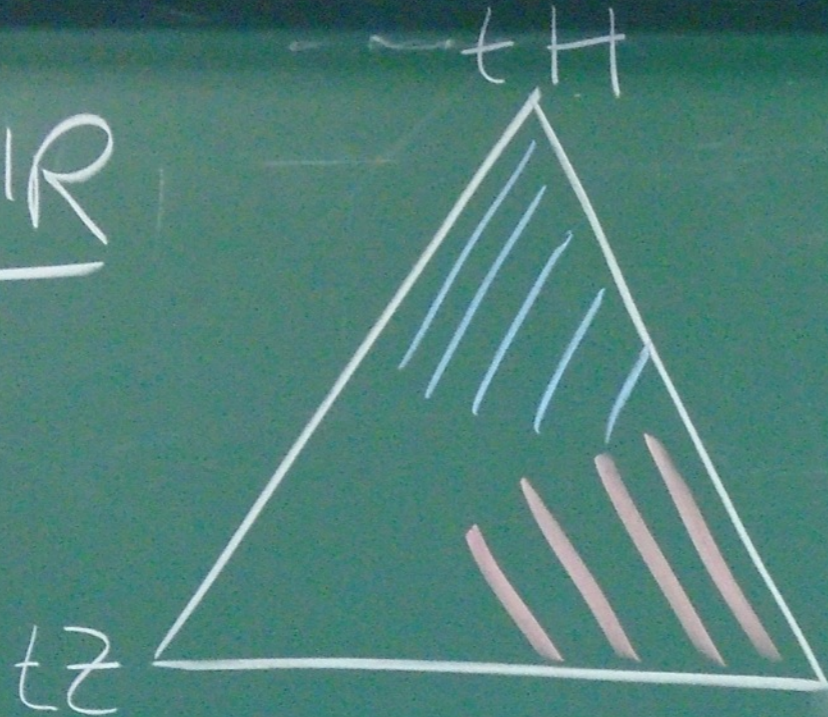
- $m(T|\text{singlet}) > 750 \text{ GeV}$ (was 765 GeV)
- $m(T|\text{doublet}) > 800 \text{ GeV}$ (was 855 GeV)
- expected limits improved by 60 GeV (singlet), 80 GeV (doublet)



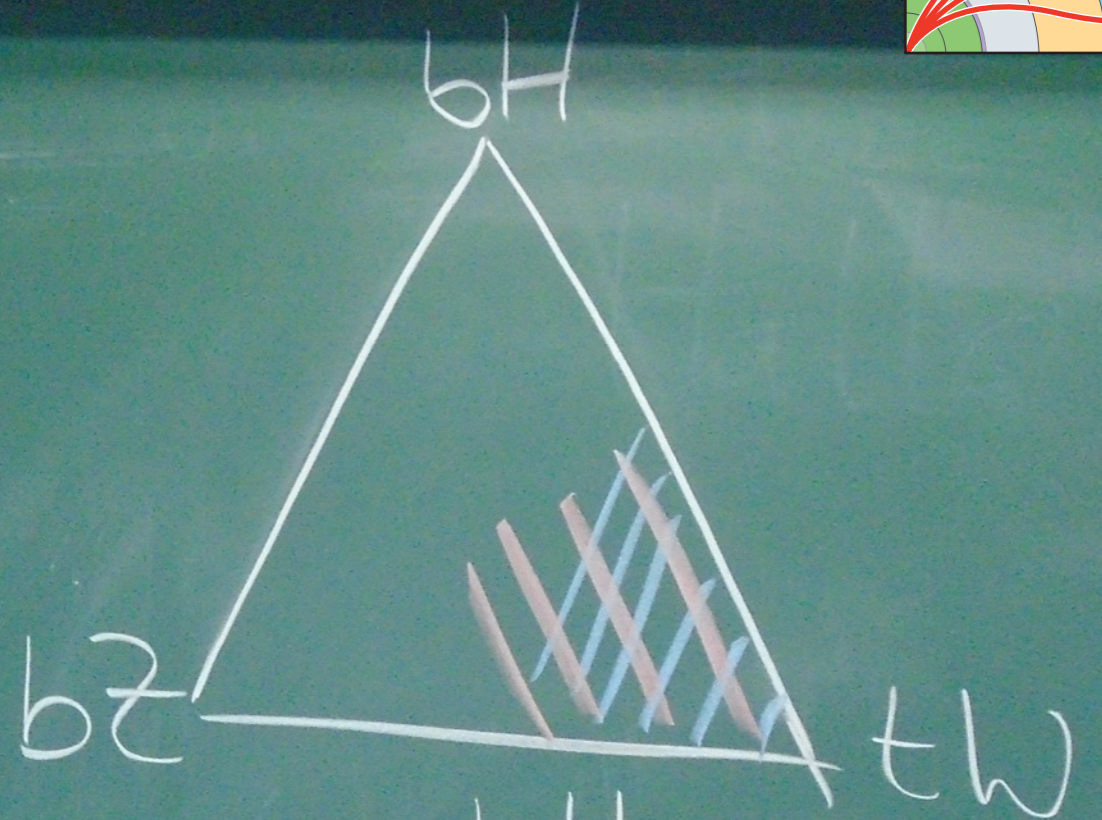
Wb+X



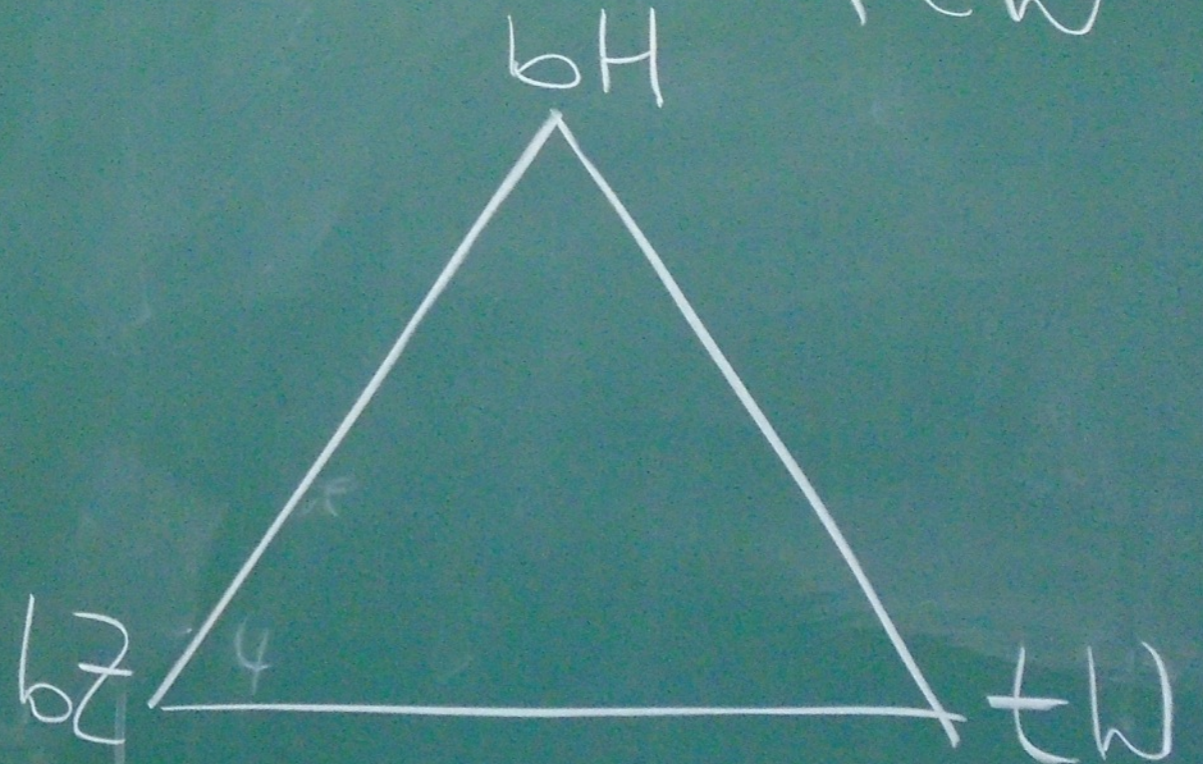
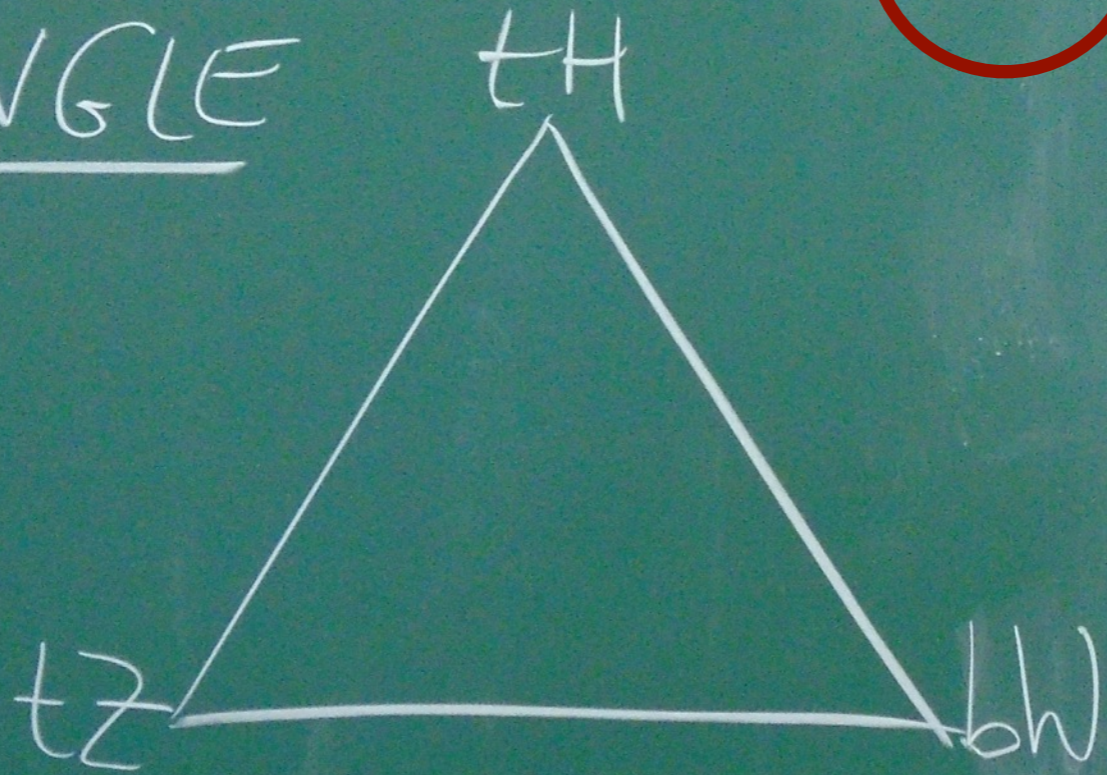
PAIR

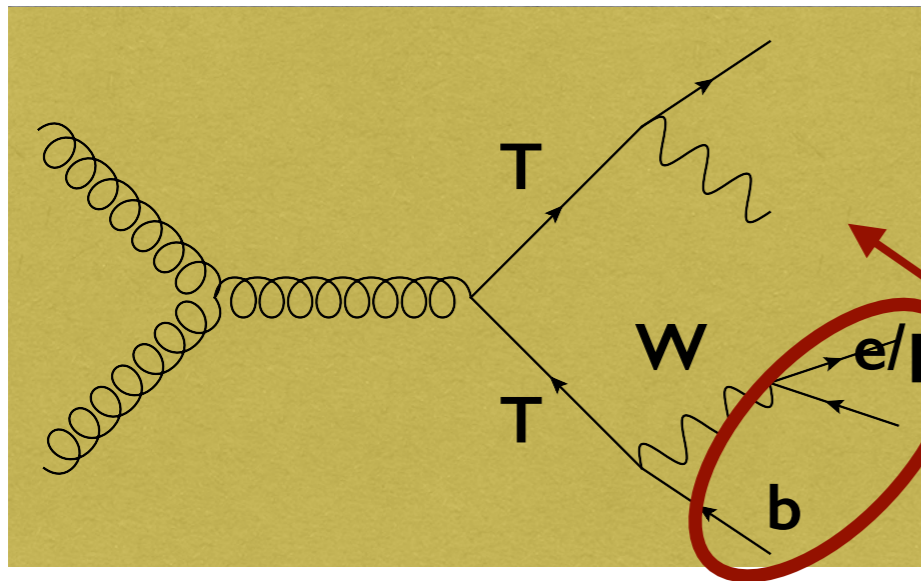
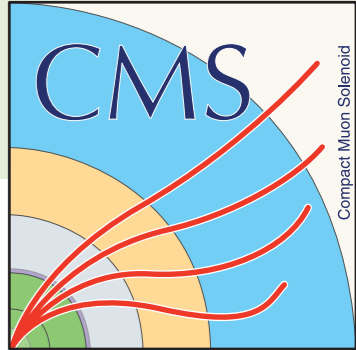


bW

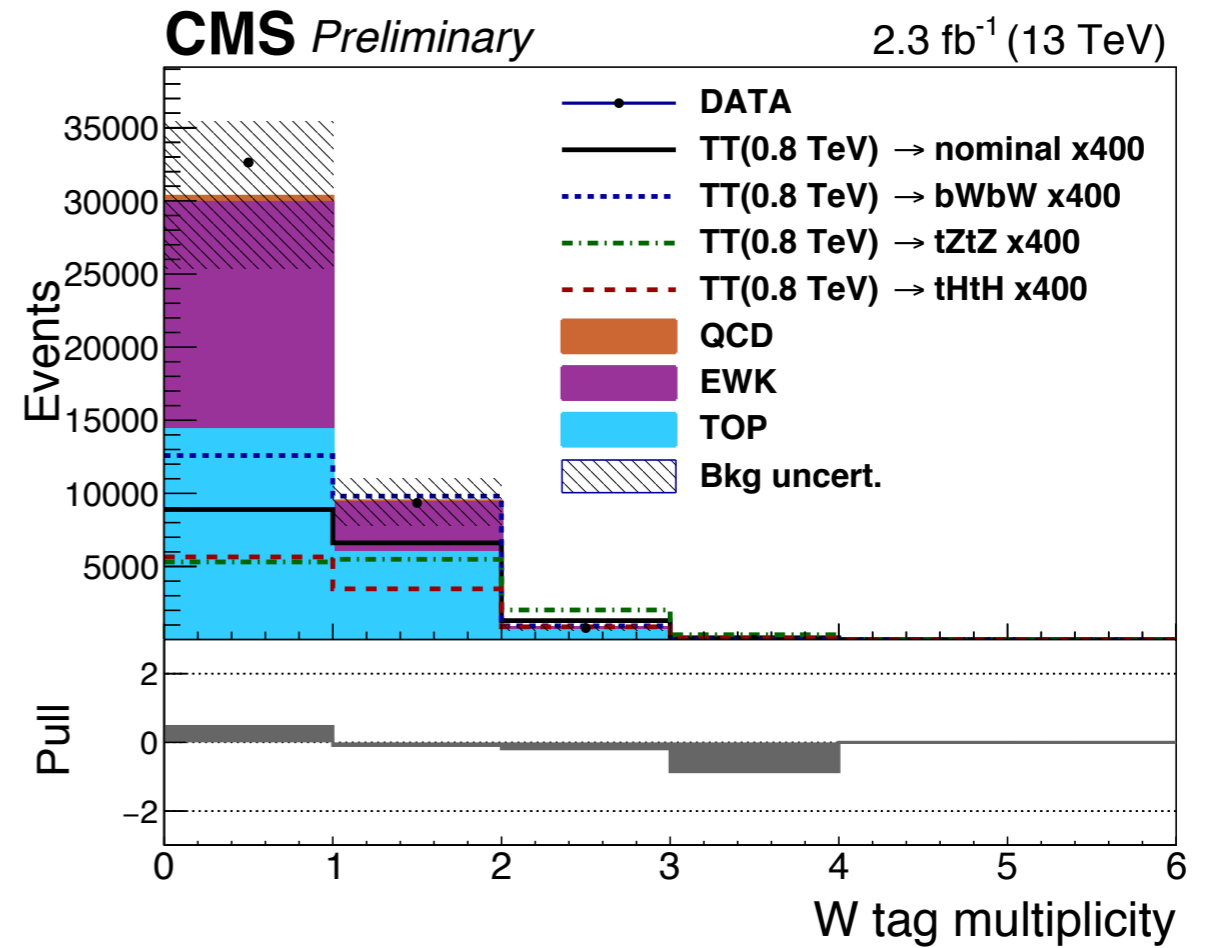
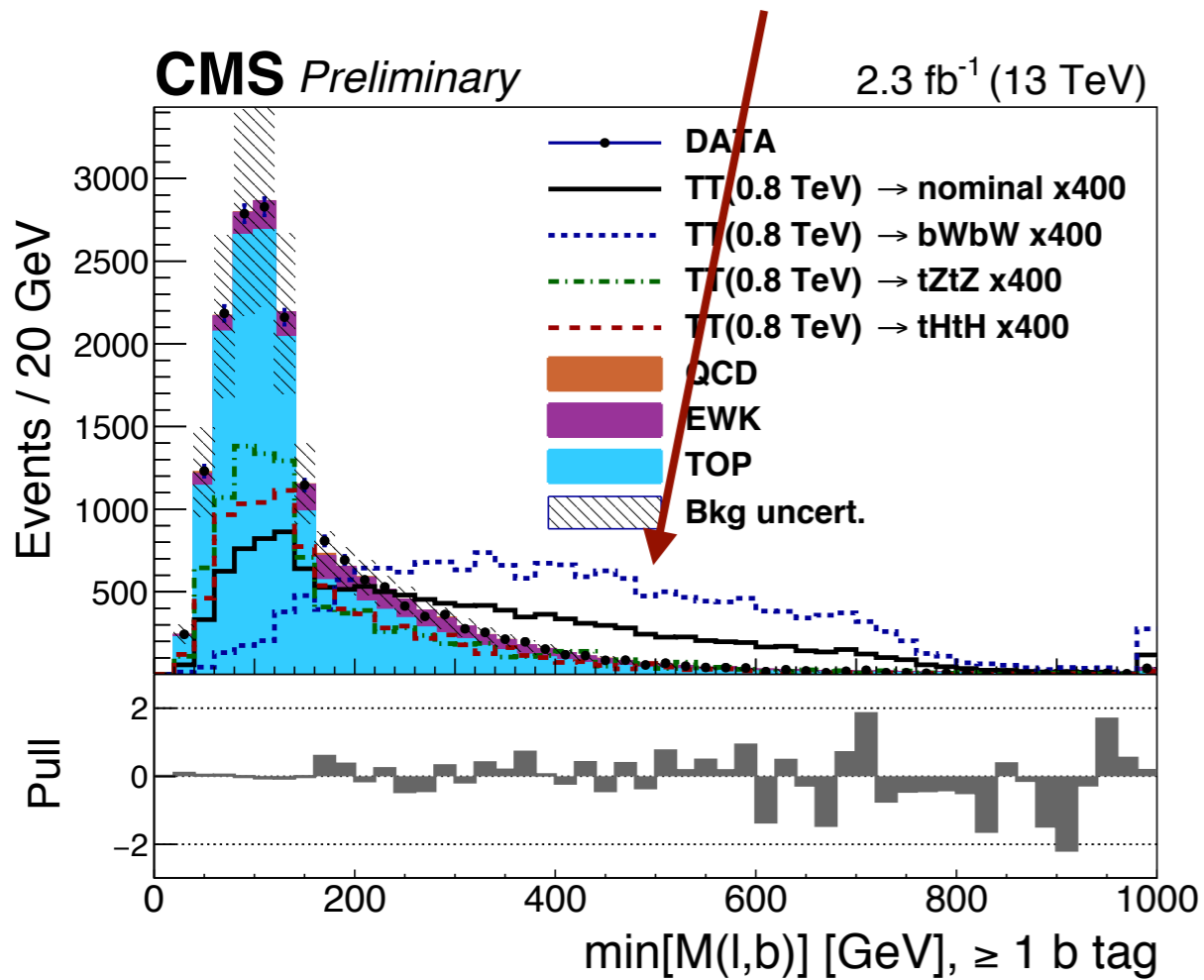


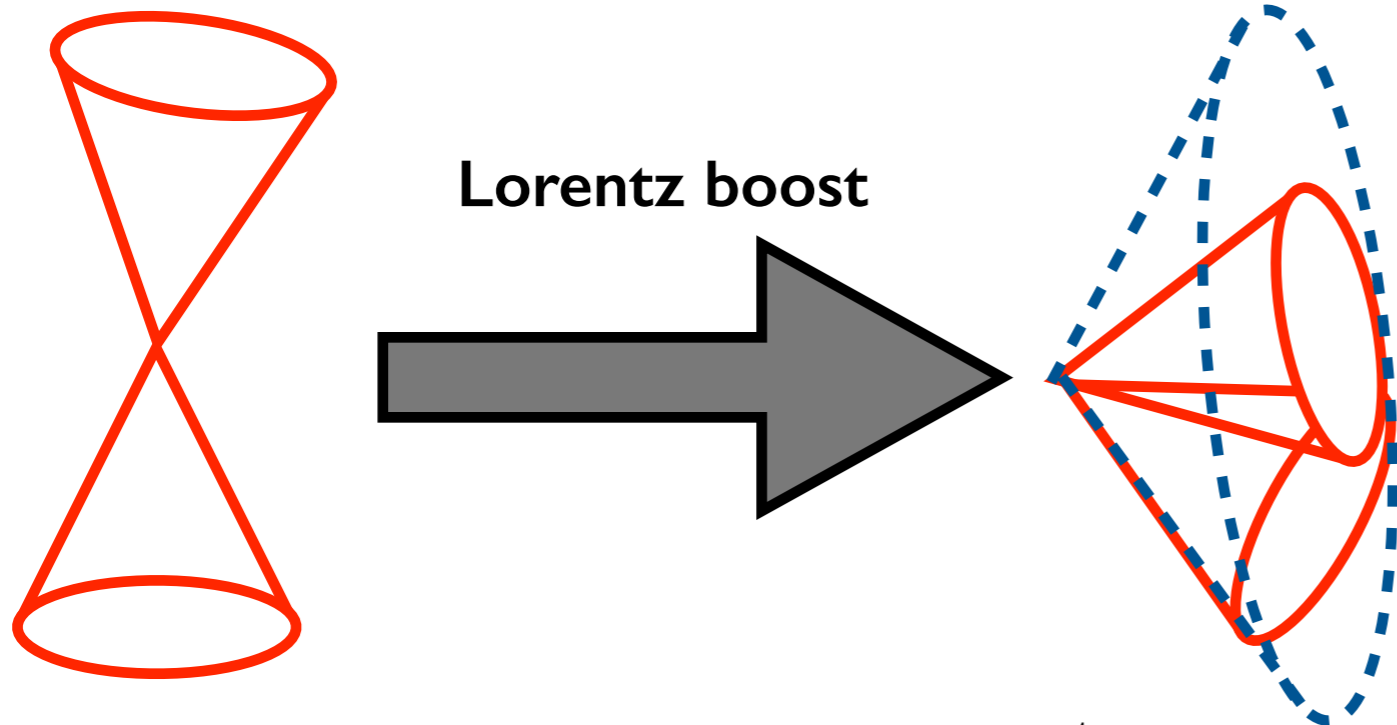
SINGLE



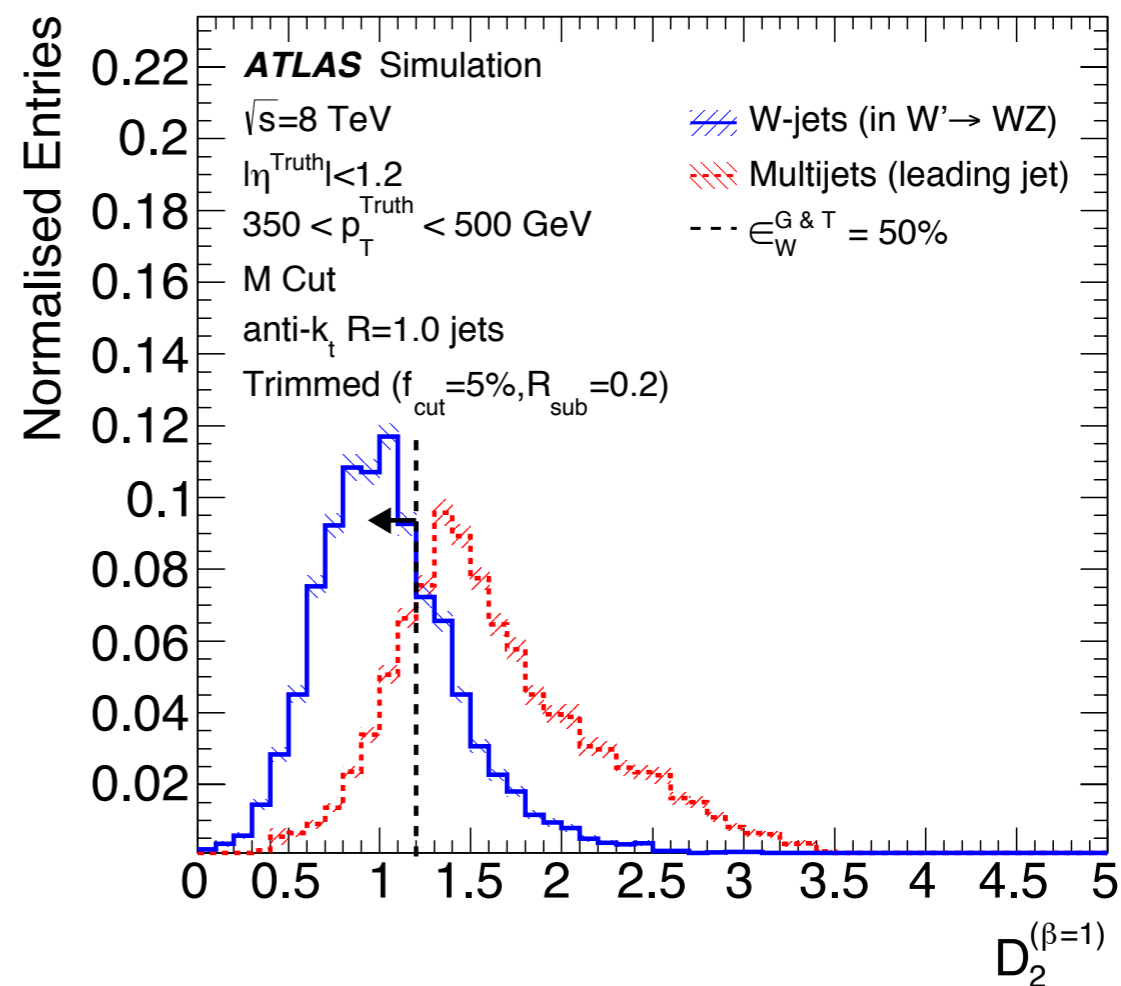
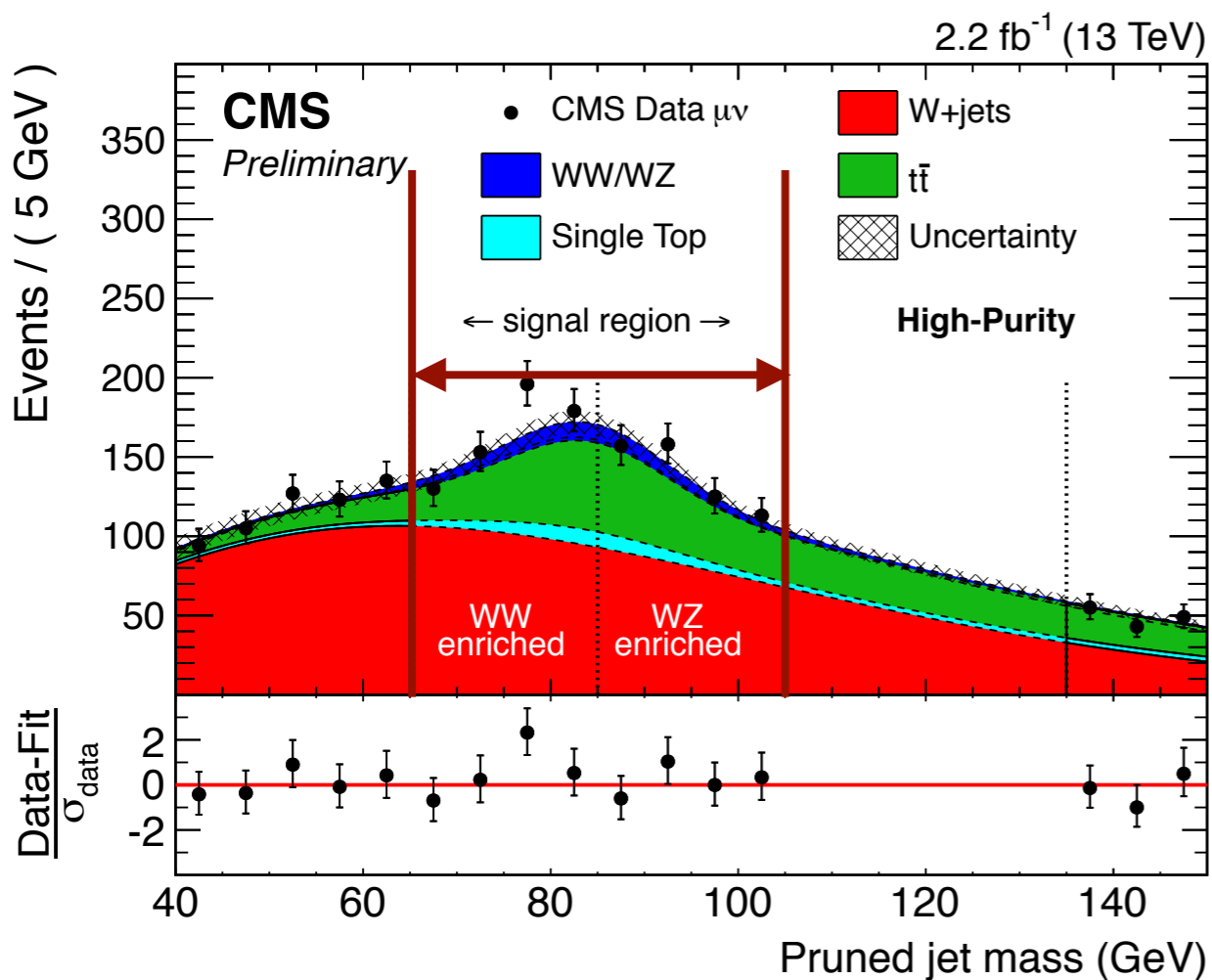


- 1 e/ μ , MET, ≥ 3 high- p_T jets
- final discriminant :
 - min(m(lb))
 - categorization in #b-tags + #W-tags from other T-branch



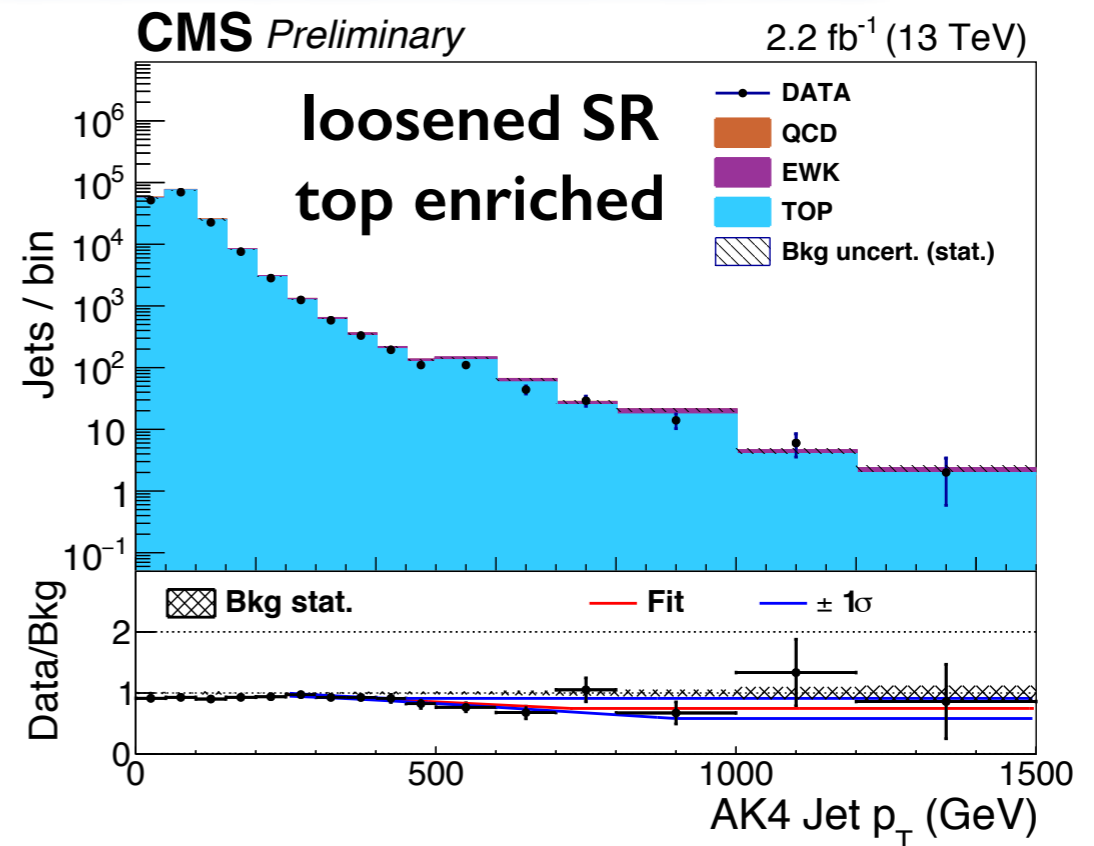
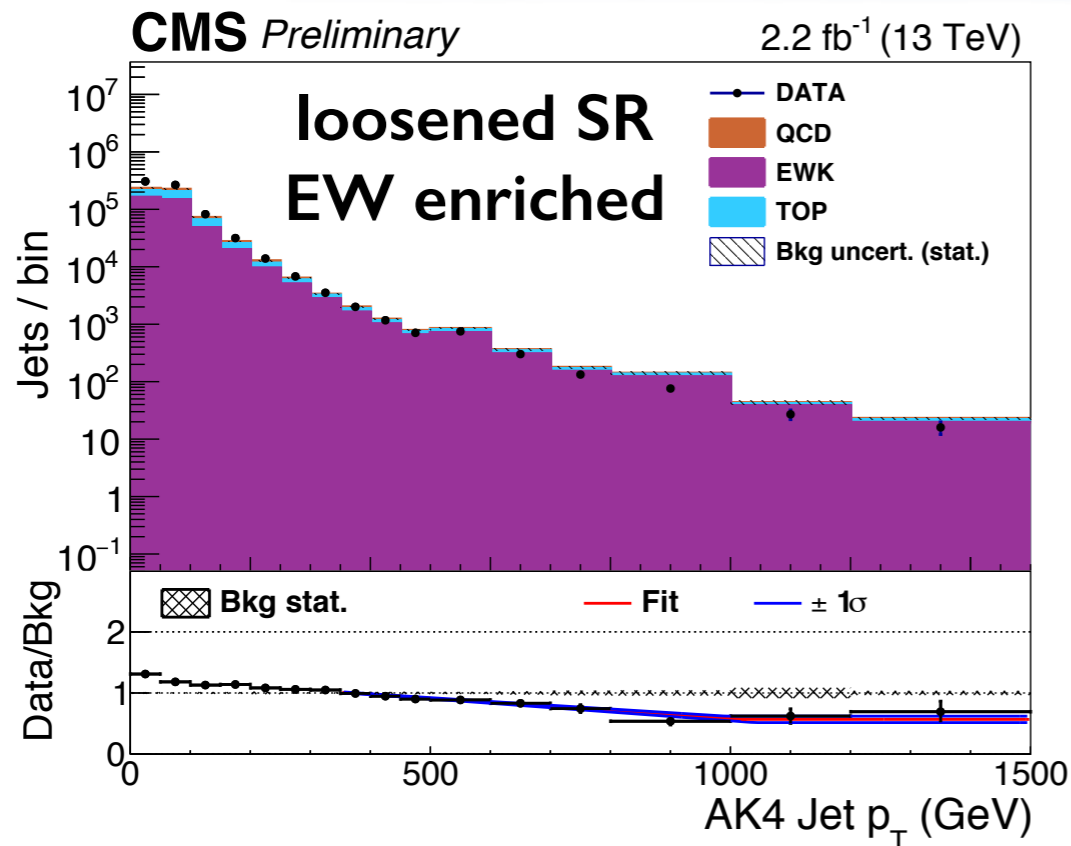
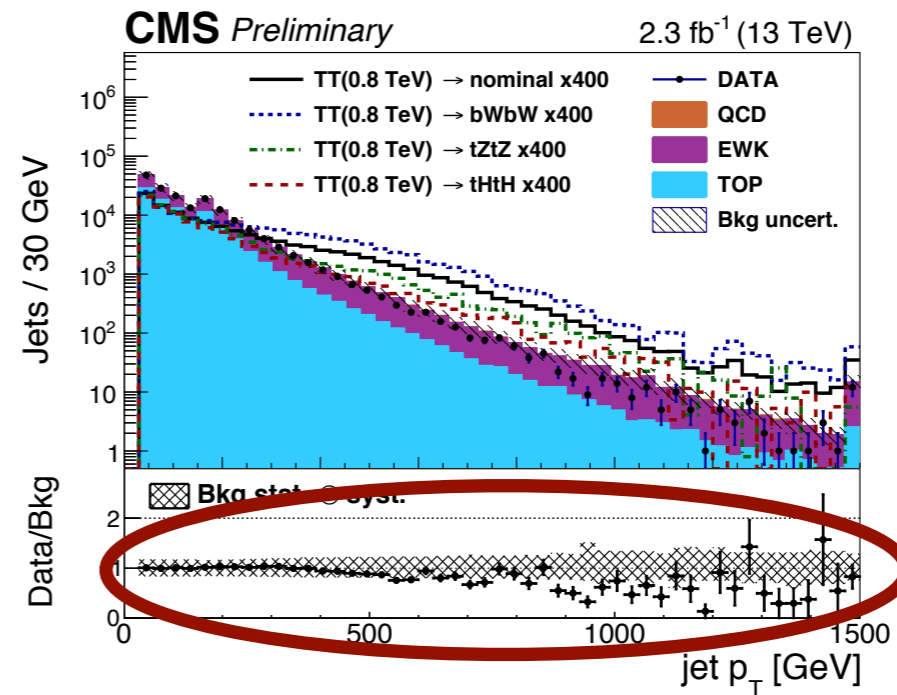


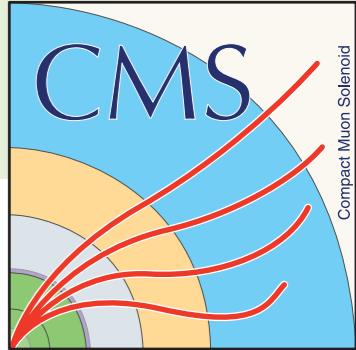
- mass window around m_W
- two-prong-sensitive variable
 - N-subjettiness (CMS)
 - energy correlation D_2 (ATLAS)



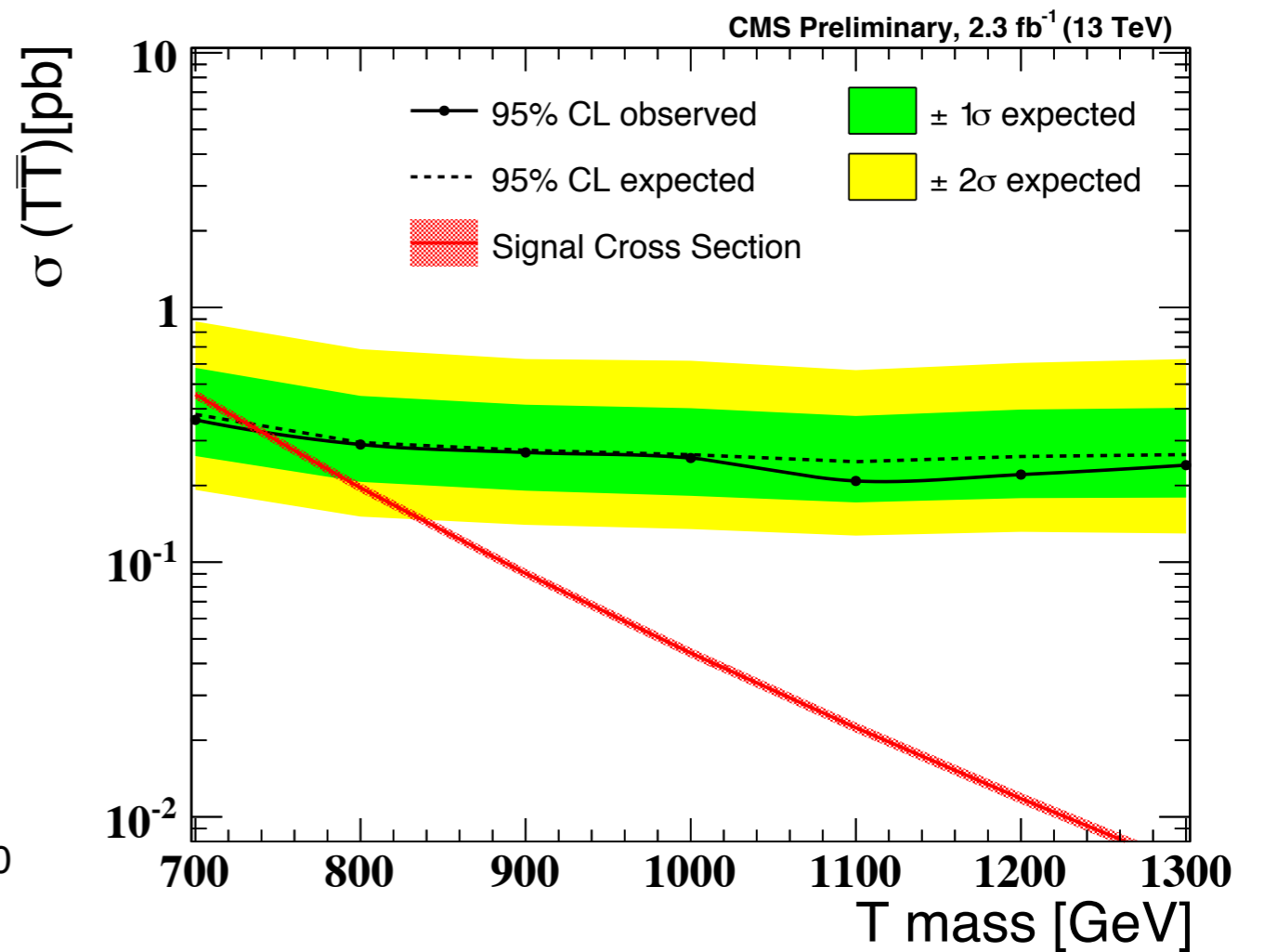
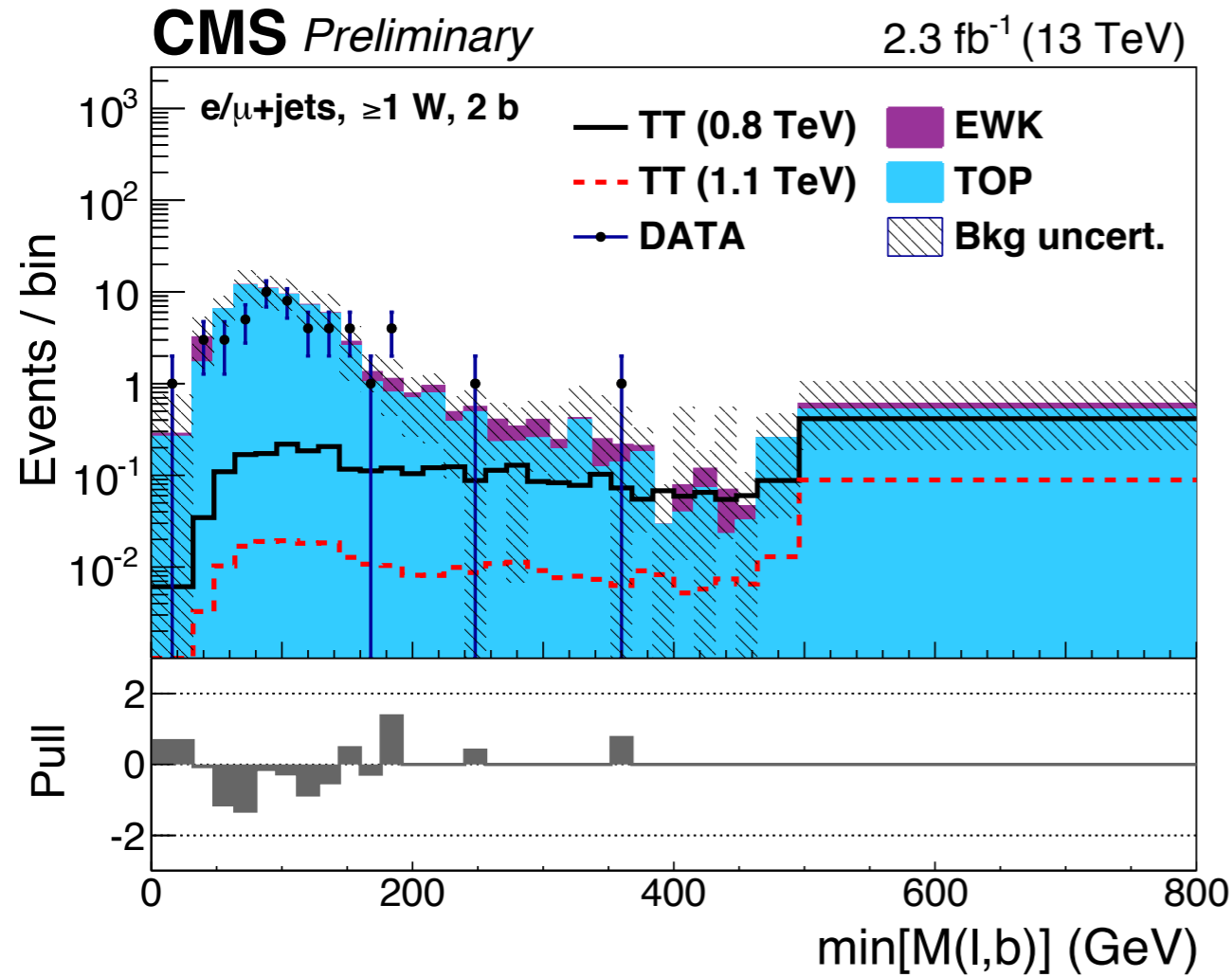
Mismodeling of jet p_T

- observed in inclusive SR
- linear correction derived
- separately for top & EW
- conservative syst. from lower statistics top CR



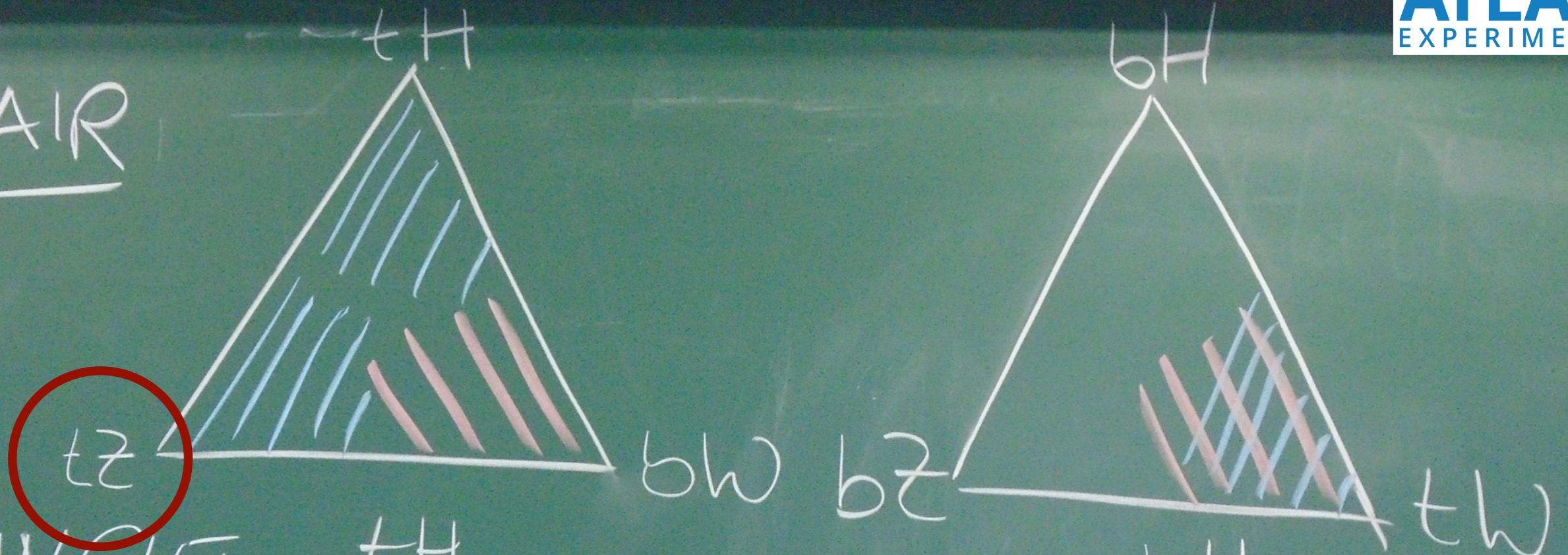


- $m(T|\text{singlet}) > 750 \text{ GeV}$ (was 696 GeV)
- $T \rightarrow Wb$ not allowed for doublet
- benchmark interpretation :
 - Wb:Zt:Ht = 50%:25%:25%

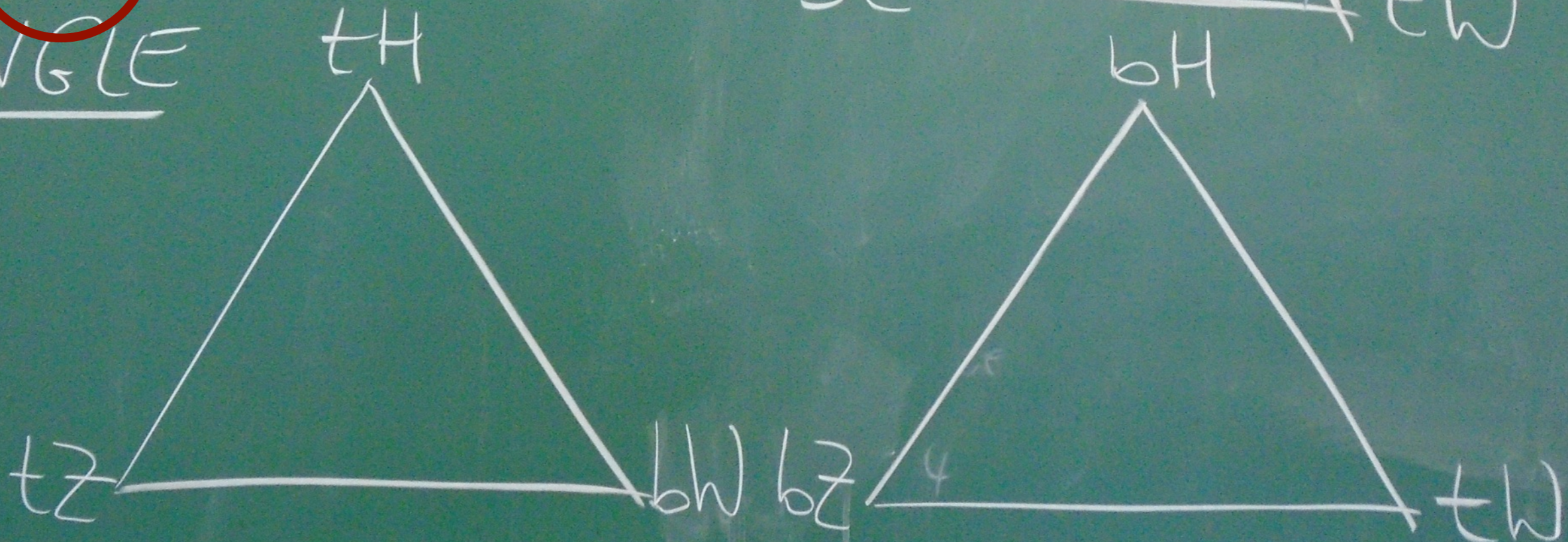


Stops and Zt+X

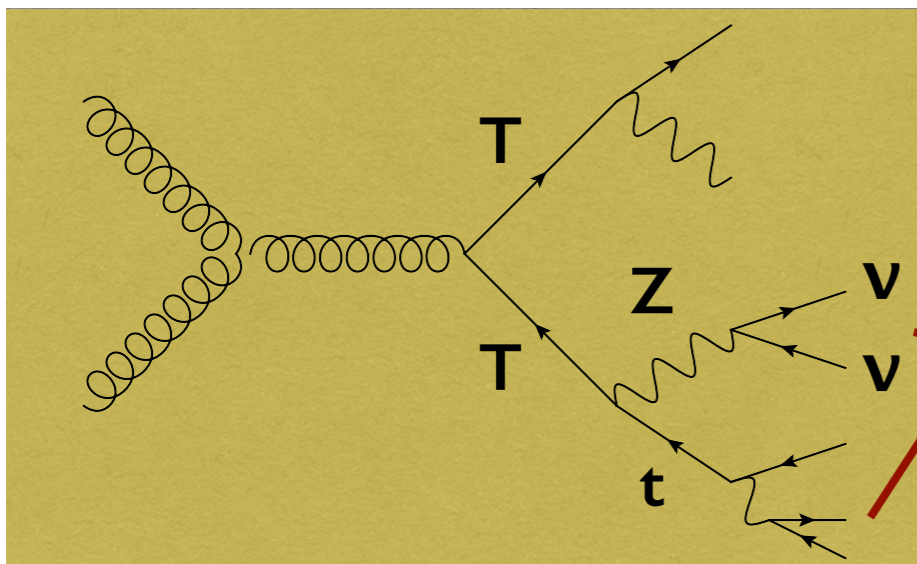
PAIR



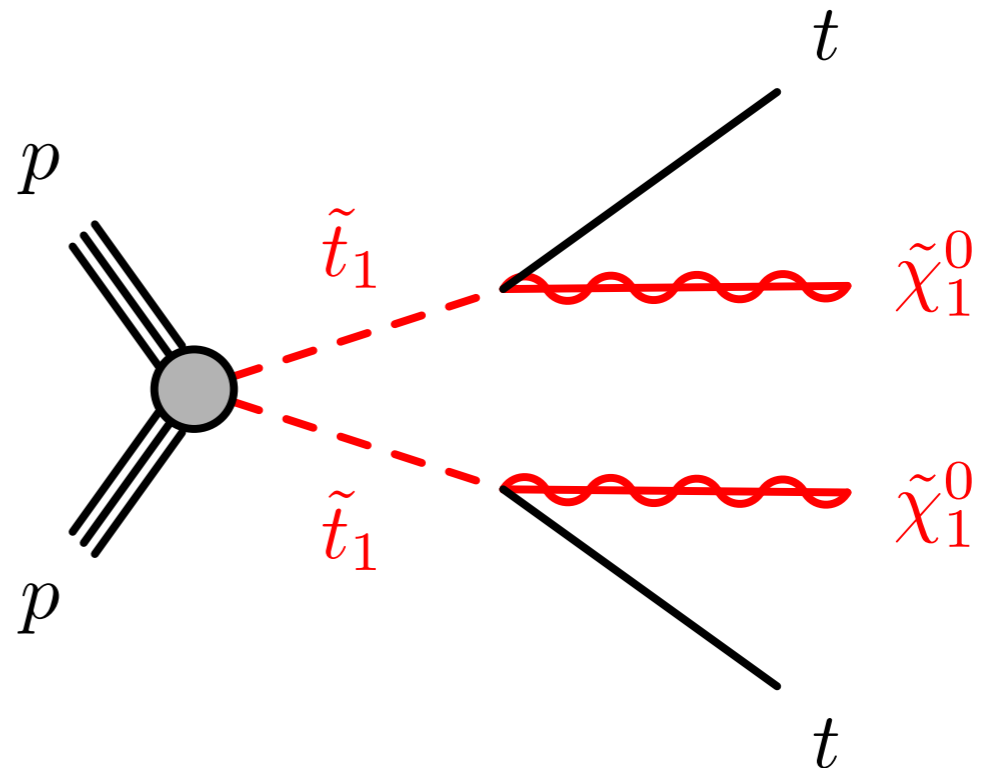
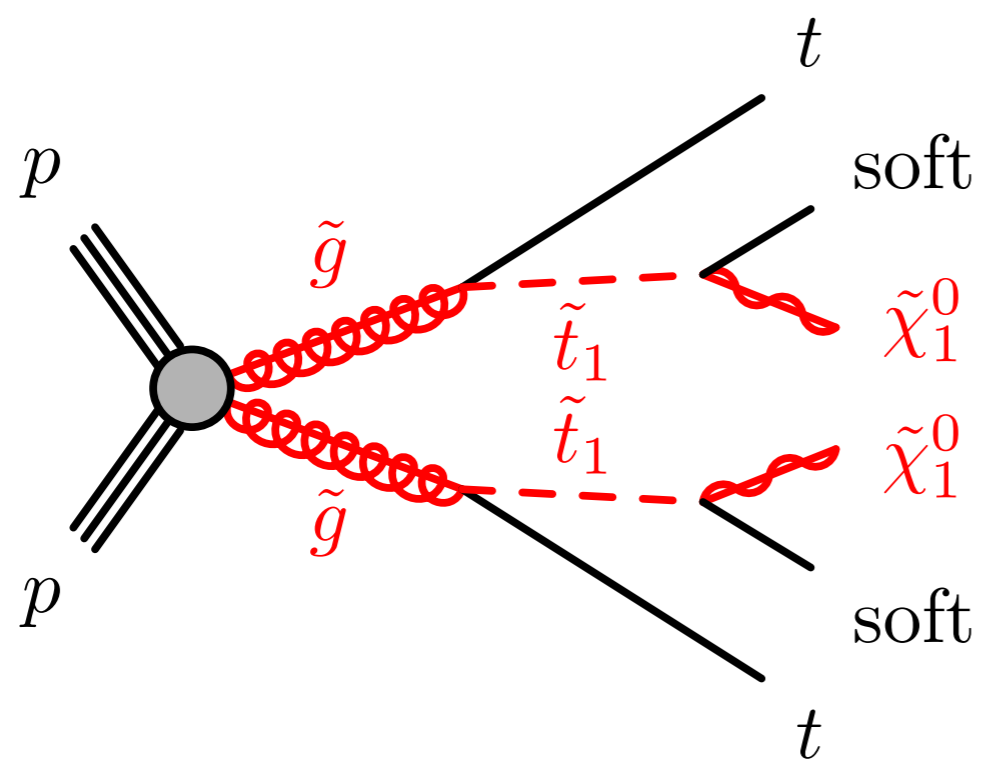
SINGLE



Stops and Zt+X



- $1 e/\mu + \geq 4$ jets
- QCD and τ vetos
- optimized SRs targeting $t\bar{t} + E_T^{\text{miss}}$ with
- MET > 260/350/480 GeV
- b-tags, large-R jet, kinematic requirements

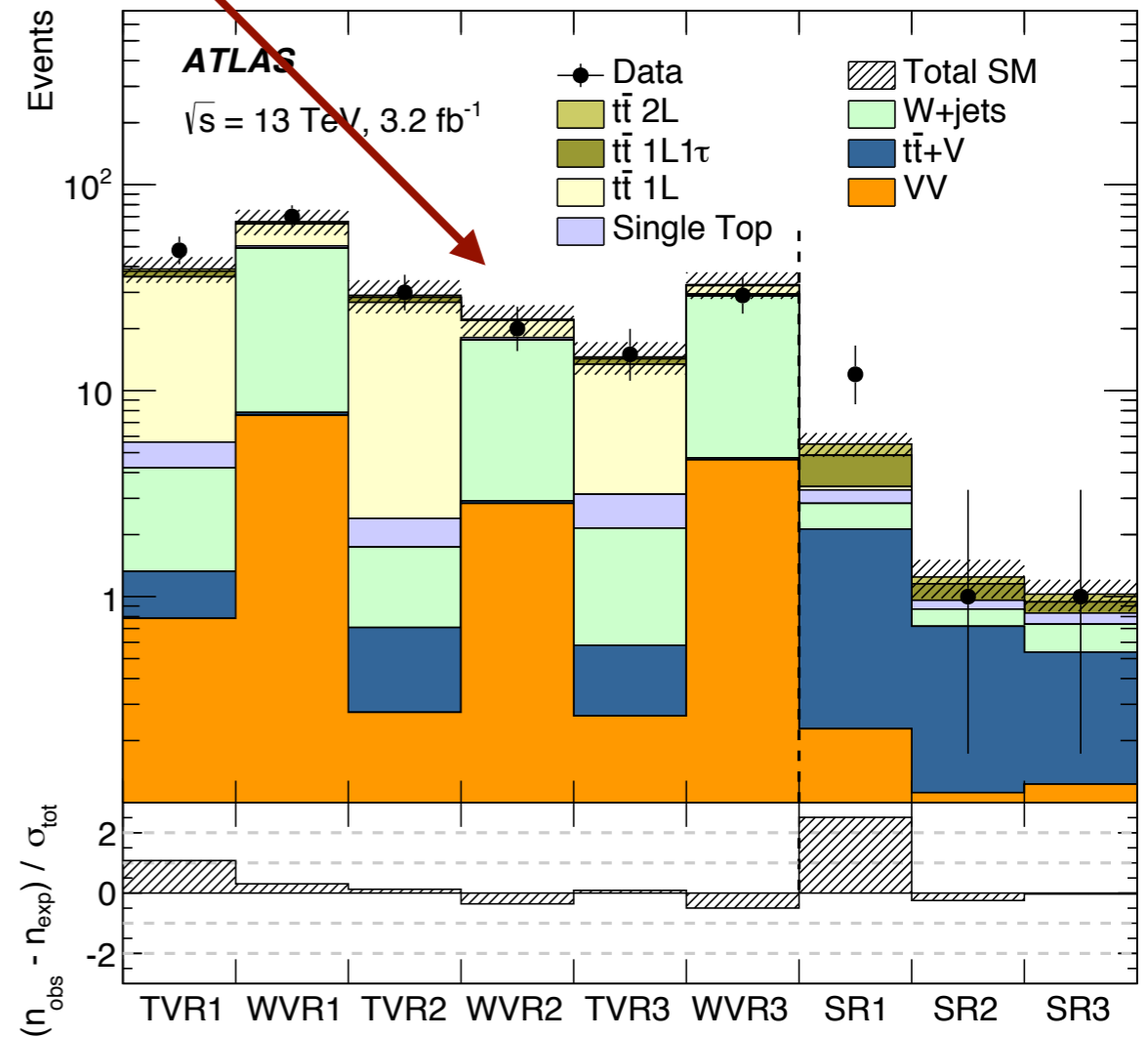
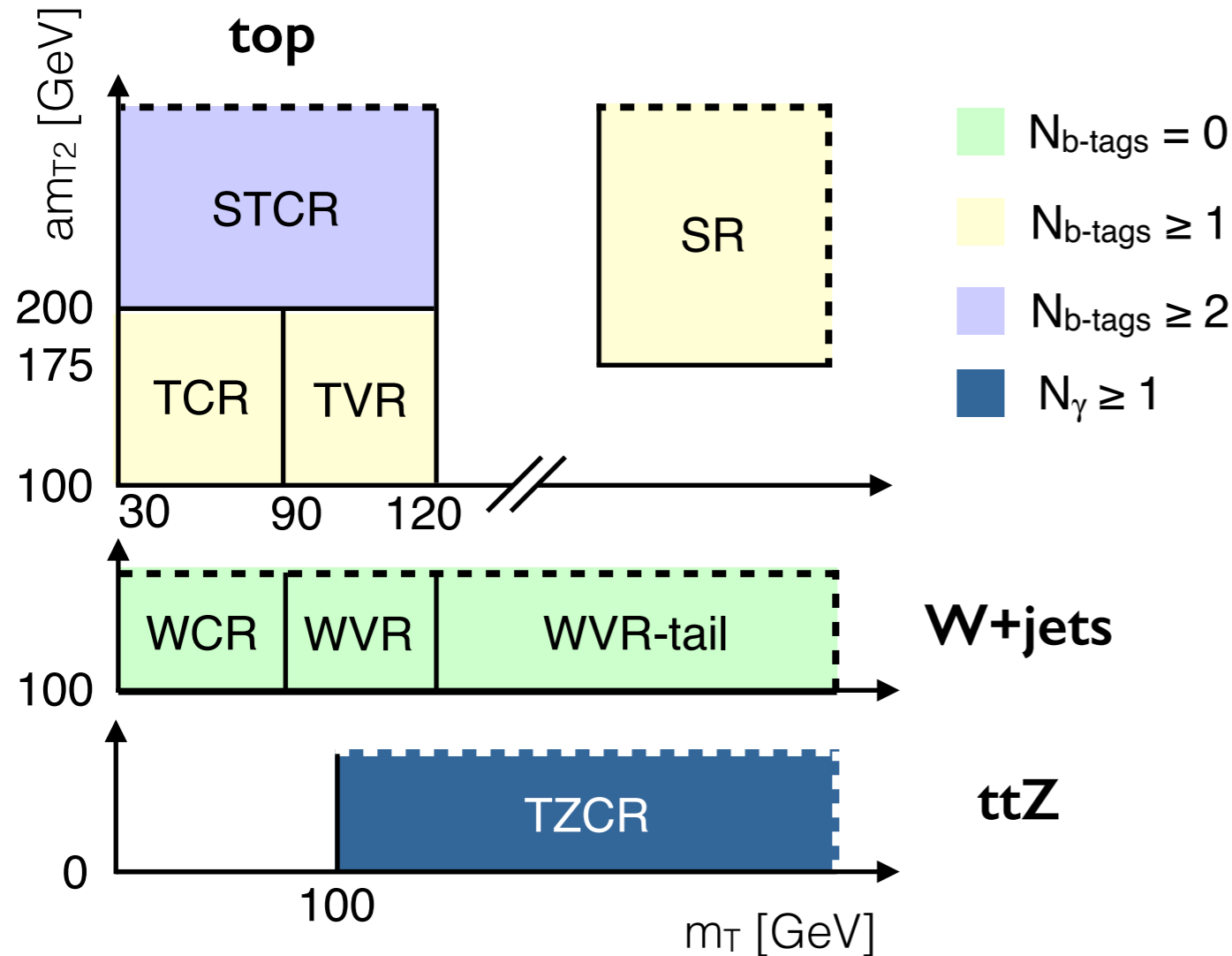


updated with 2016 data in ATLAS-CONF-2016-050
(but w/o VLQ interpretation)

Stops and Zt+X

'SUSY-style analysis strategy'

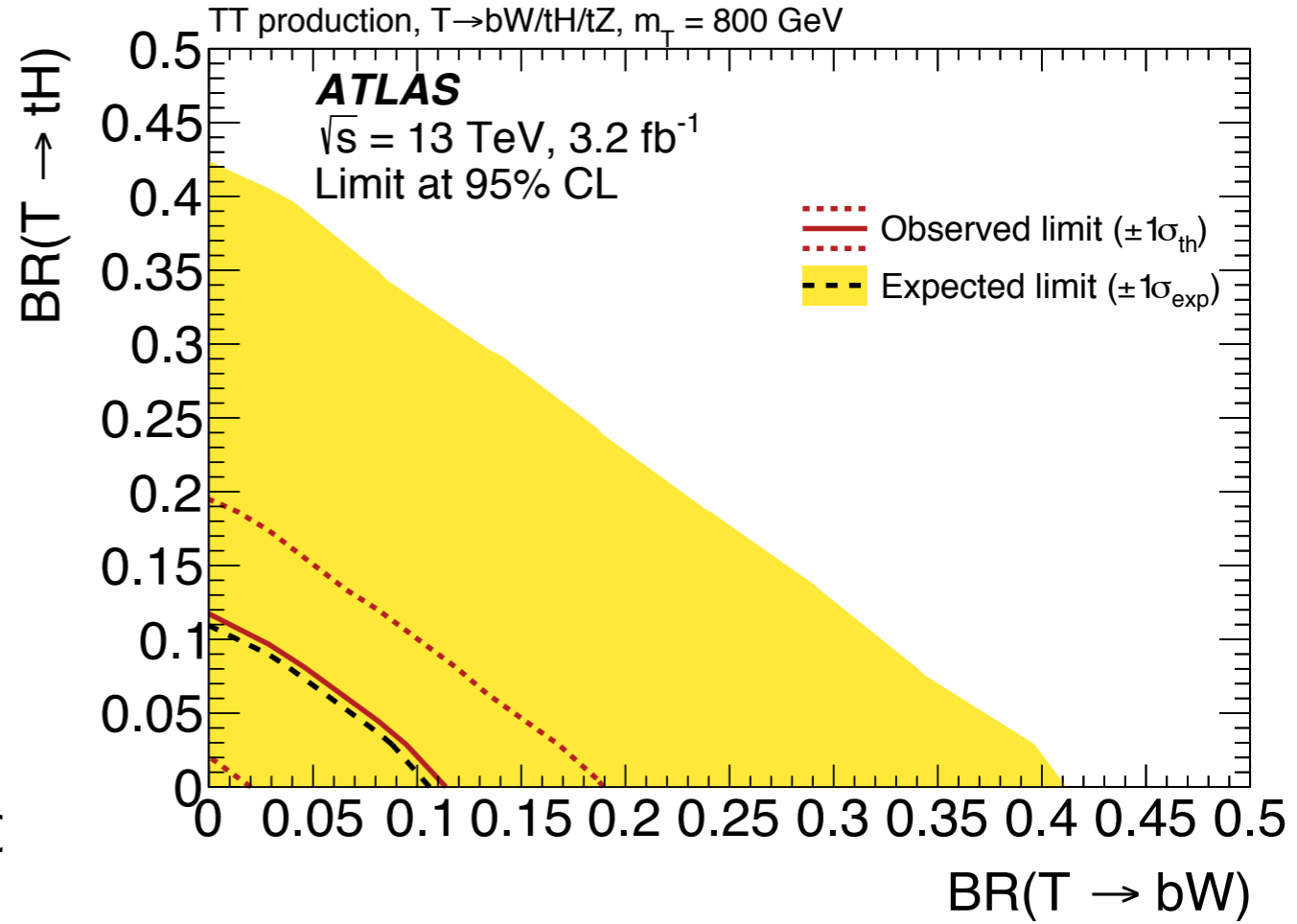
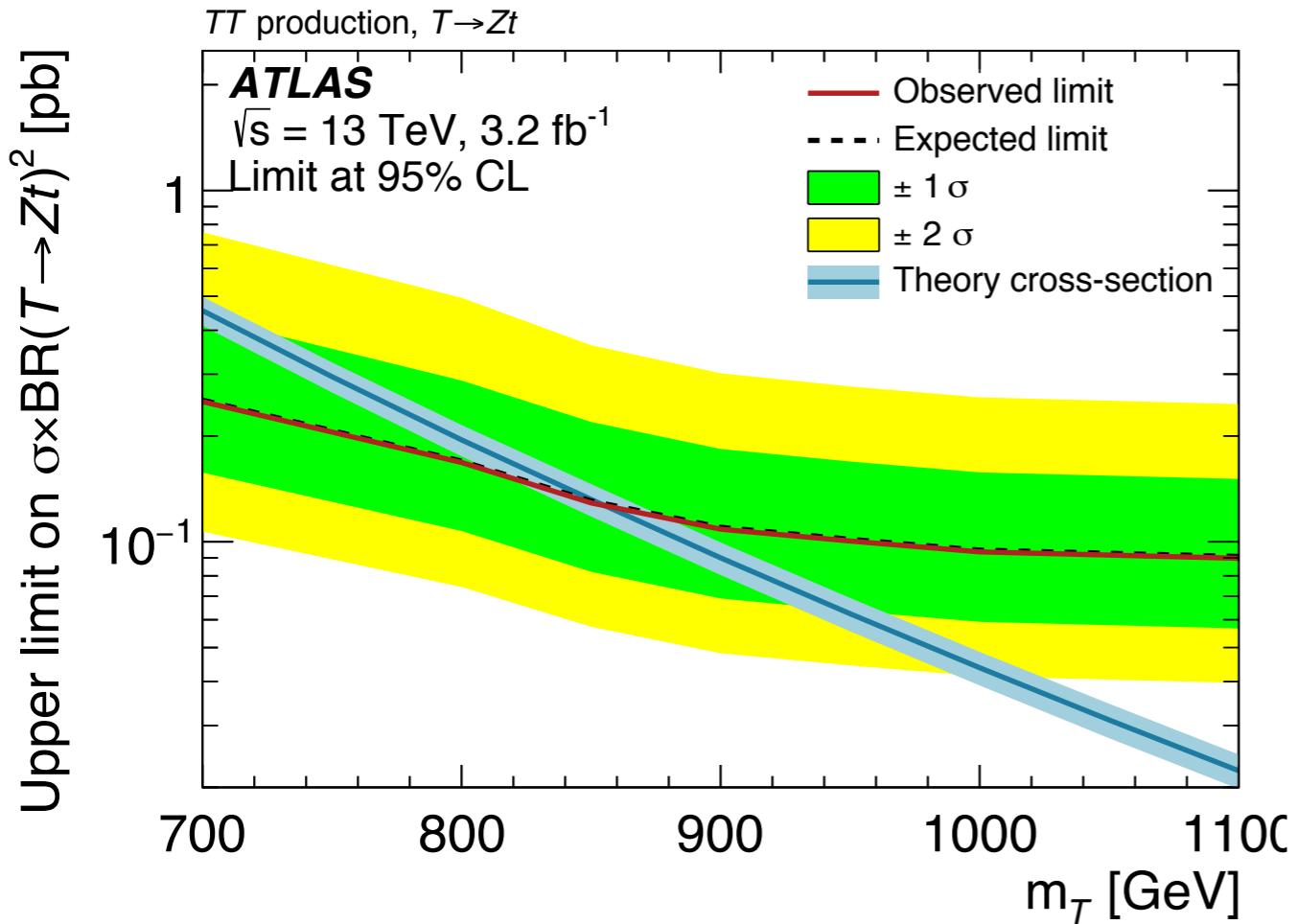
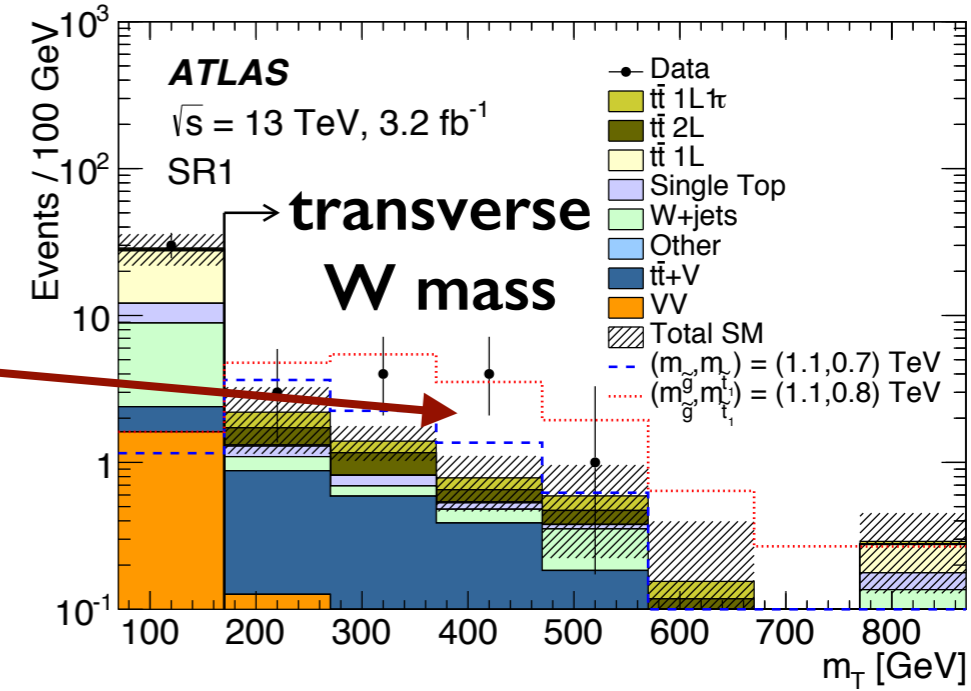
- 3 SRs defined
- each SR fitted with several CRs for main backgrounds
- fit validated in VRs — overall yields consistent



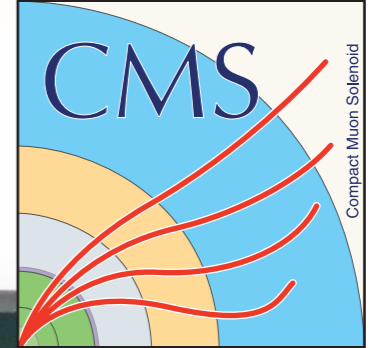
Stops and Zt+X

arXiv:1606.03903, submitted to PRD (06/16)

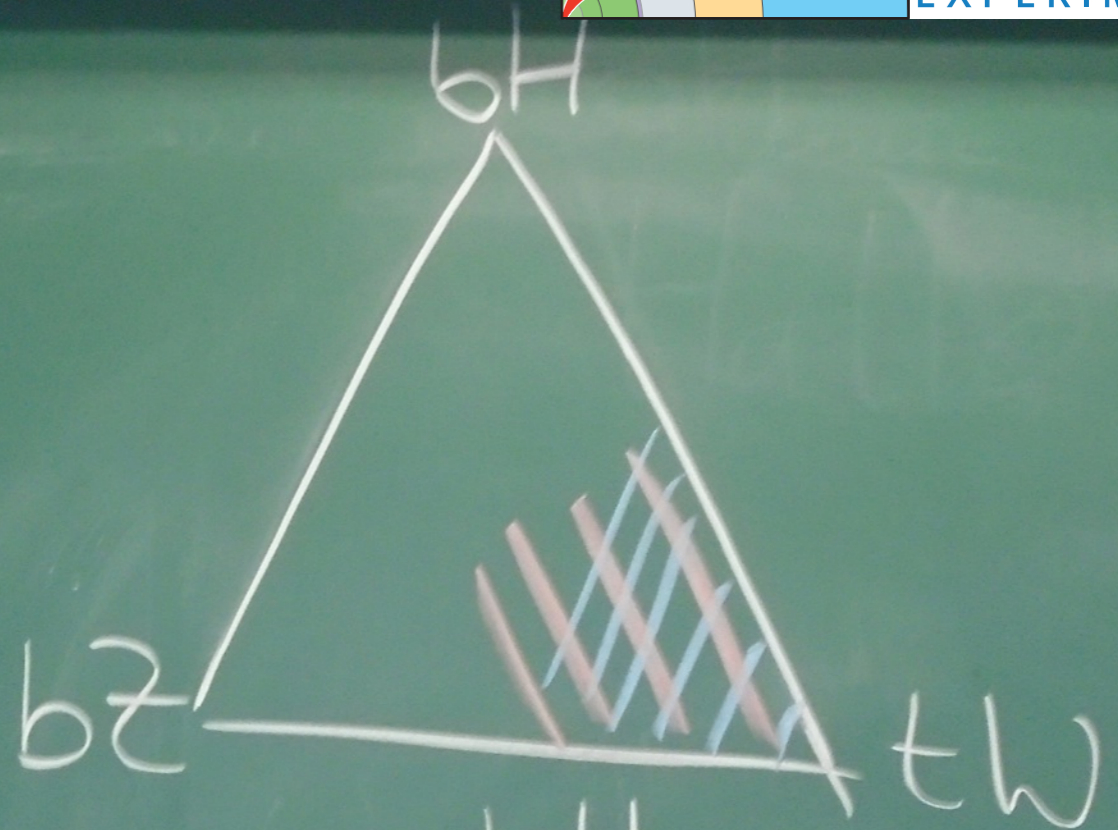
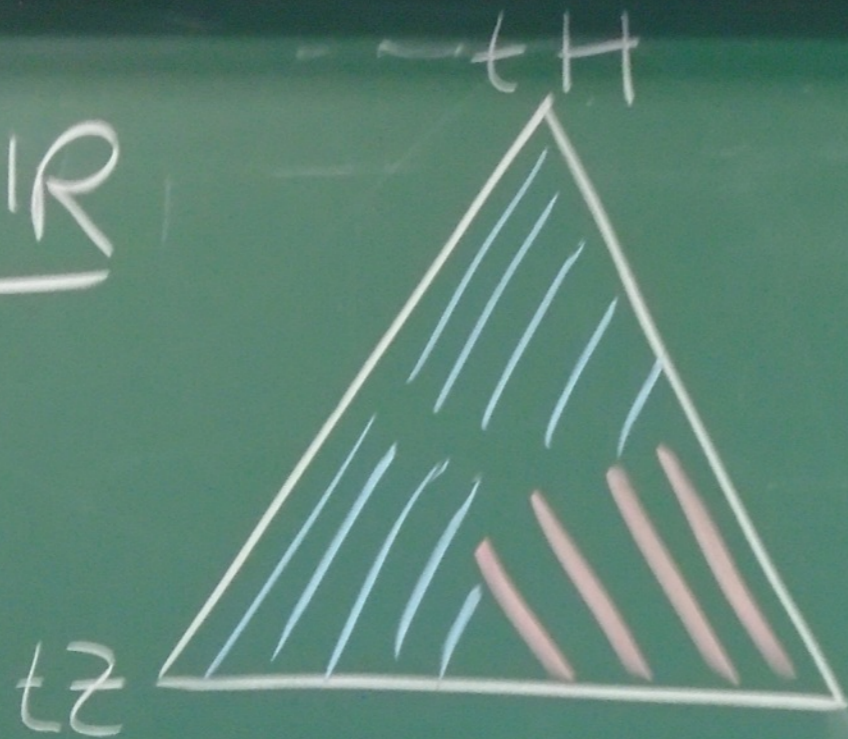
- $m(T|BR=100\%) > 850 \text{ GeV}$
(was 810 GeV in dilepton analysis)
- stat. fluctuation in SR1 *not* VLQ-like
- valuable reinterpretation
- new search channel



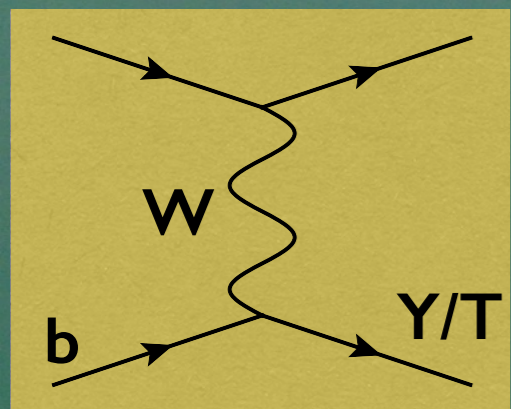
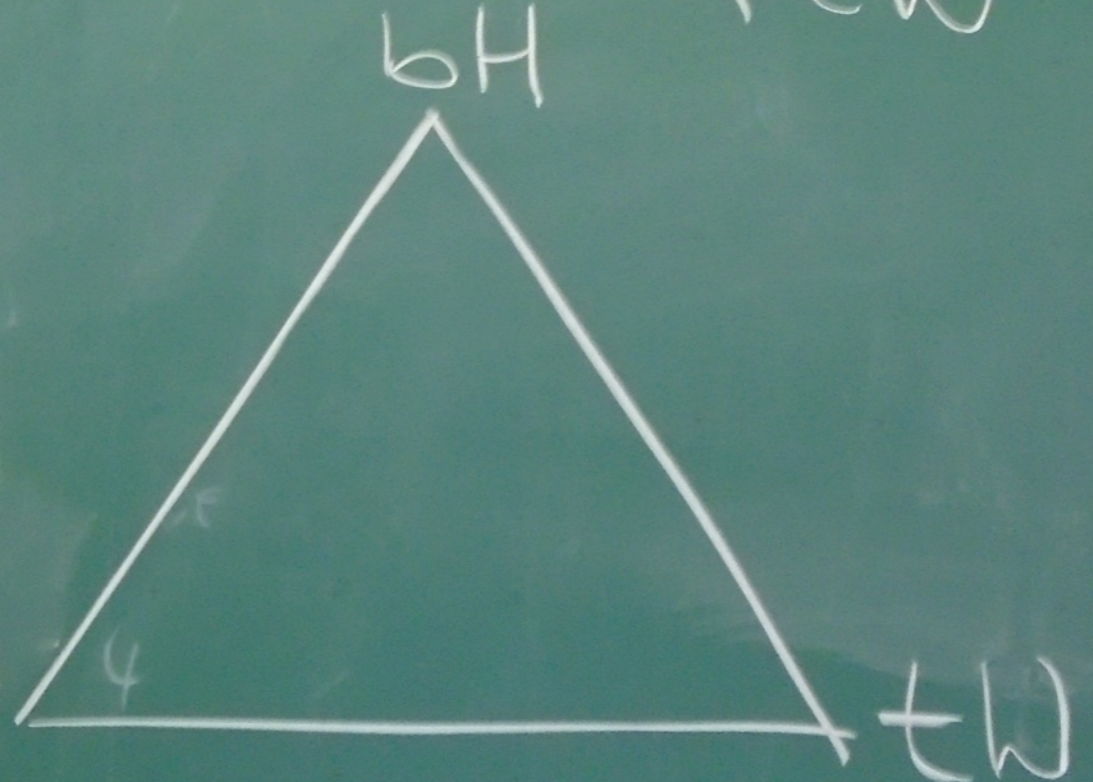
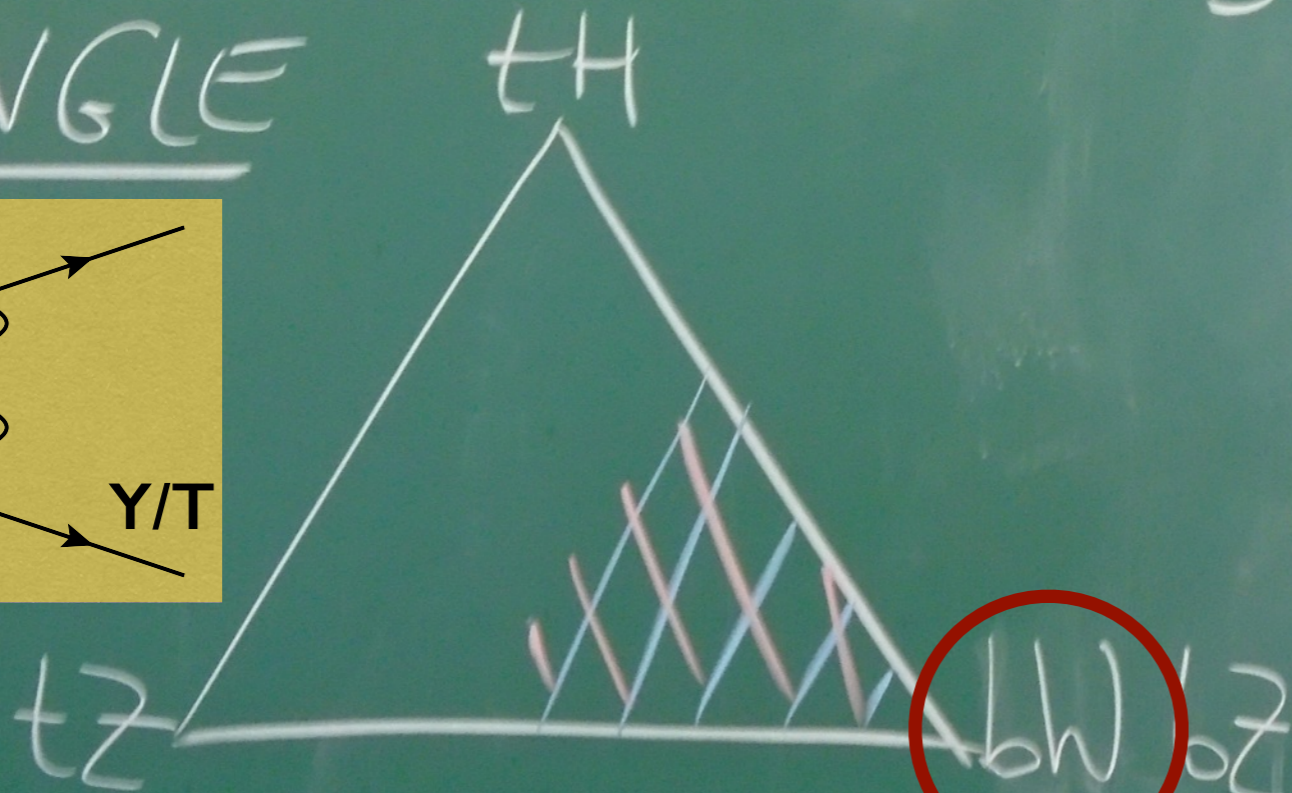
Single VLQ \rightarrow Wb



PAIR

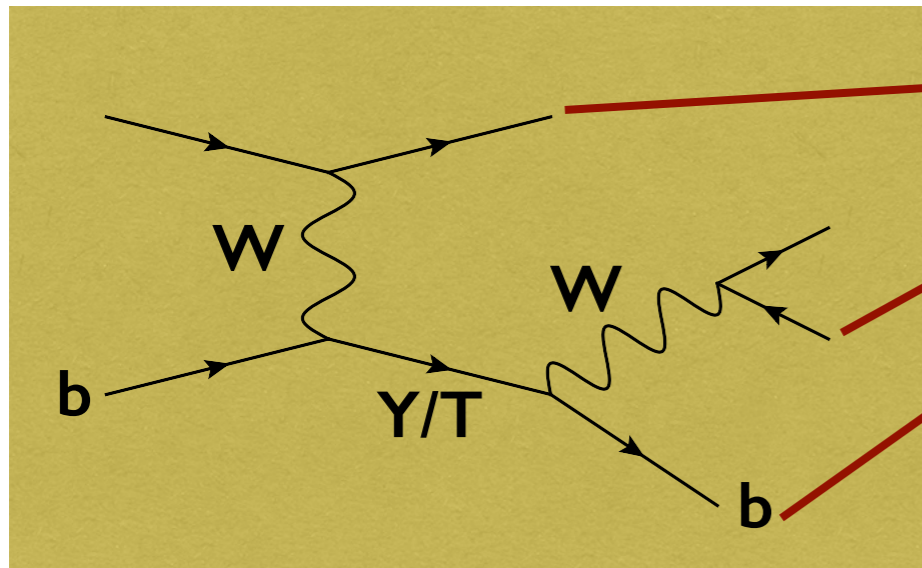


SINGLE

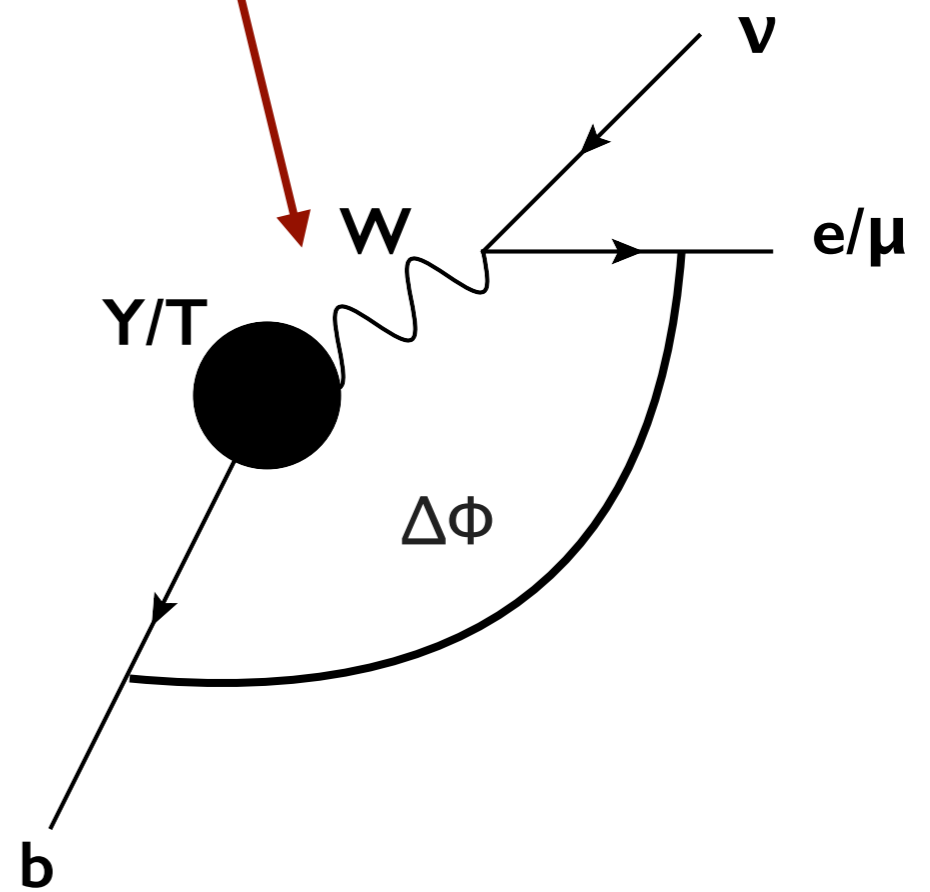
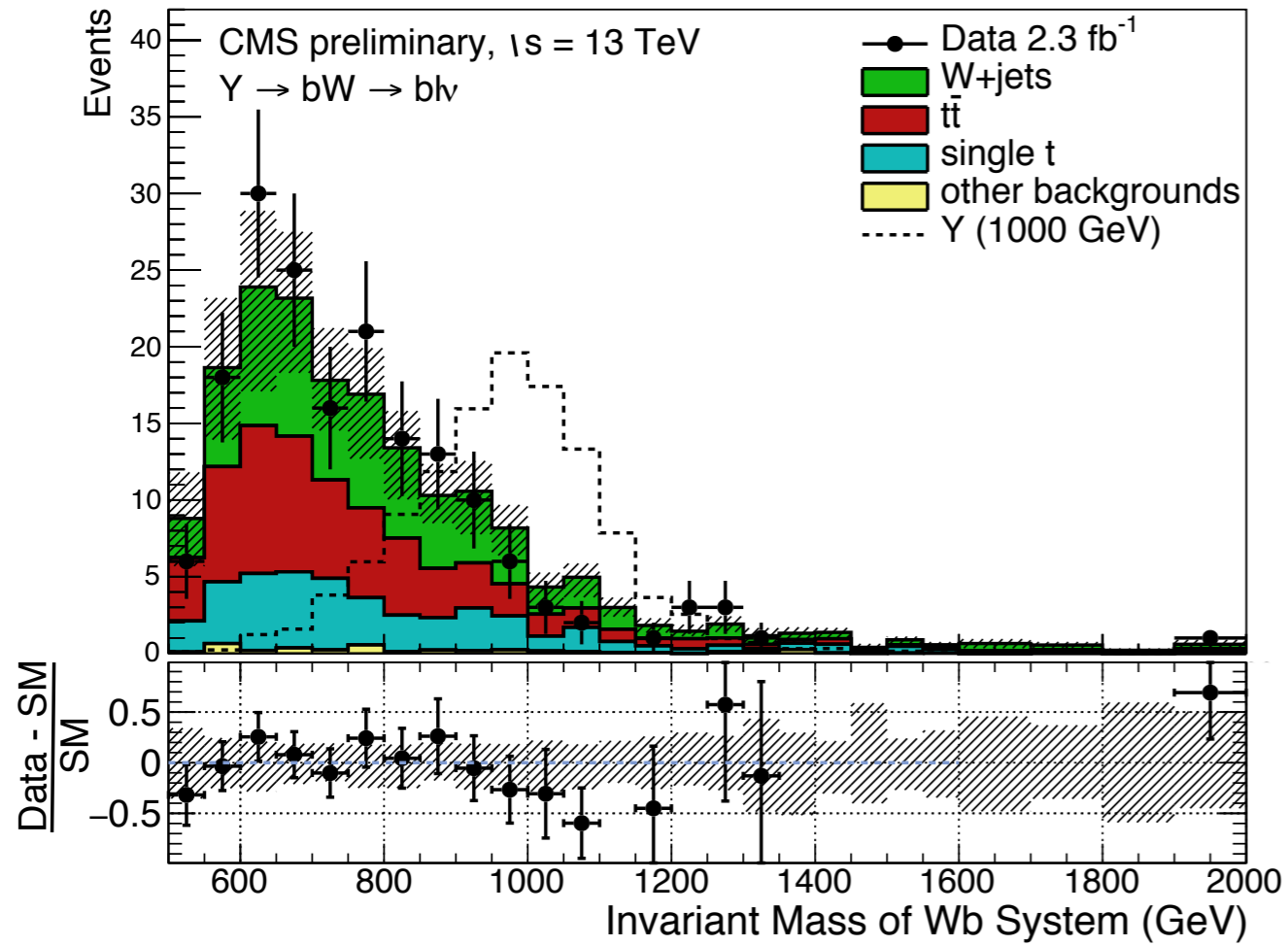


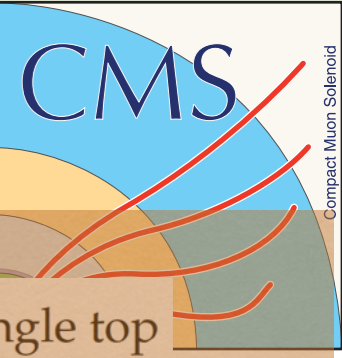
Single VLQ \rightarrow Wb

CMS PAS B2G-16-006 (07/16)



- ≥ 1 forward jet
- $= 1$ e/ μ + tight veto on 2nd lepton
- ≥ 1 high- p_T central jet with b-tag
- high MET & $S_T = p_T^l + E_T^{\text{miss}} + p_T^{\text{b-jet}}$
- W-like $m_T(W)$ & $\Delta\Phi(\text{lep.}, b) > 2.0$





Single VLQ \rightarrow Wb

CMS PAS B2G-16-006 (07/16)

CMS PAS TOP-16-005

Measurement of the top quark pair production cross section using $e\mu$ events in proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS detector

$$\sigma_{t\bar{t}} = 793 \pm 8 \text{ (stat)} \pm 38 \text{ (syst)} \pm 21 \text{ (lumi)} \text{ pb}$$

CMS PAS TOP-16-003

Measurement of the inclusive cross section of single top quark production in the t channel at $\sqrt{s} = 13$ TeV

$$\sigma_{t\text{-ch.}} = 227.8 \pm 9.1 \text{ (stat.)} \pm 14.0 \text{ (exp.)} {}^{+28.7}_{-27.7} \text{ (theo.)} \pm 6.2 \text{ (lumi.)} \text{ pb}$$

source		W+Jets	$t\bar{t}$	Single Top	Signal
Luminosity	rate	2.7%	2.7 %	2.7 %	2.7 %
Jet energy scale	shape	5%	6%	5%	3%
Jet energy resolution	shape	2%	1%	1%	2%
B-tagging efficiency	shape	3%	5%	5%	5%
Multiple interactions	shape	1%	1%	1%	1%
Lepton ID/ISO scale factor	rate	2%	2%	2%	2%
Trigger efficiency	rate	2%	2%	2%	2%
Cross Section	rate	9.2%	5.6%	14.7%	—
8 TeV differential linear correction \rightarrow Top P_T reweighting	shape	—	38%	—	—
8 TeV differential linear correction \rightarrow W+jets H_T reweighting	shape	5.3%	—	—	—
Q^2 Scale	shape	14%	16%	16%	25%
PDF	shape	5.5%	2.3%	8.5%	6.7%
data/MC difference \rightarrow Forward jet reweighting	rate	15%	15%	15%	15%

- Main background Xsec uncertainties from 13 TeV measurements !
- No need to correlate w/ other systematics, as scale, fwd. jet & top p_T reweighting dominate

CMS PAS SMP-15-004

Measurement of inclusive W and Z boson production cross sections in pp collisions at $\sqrt{s} = 13$ TeV

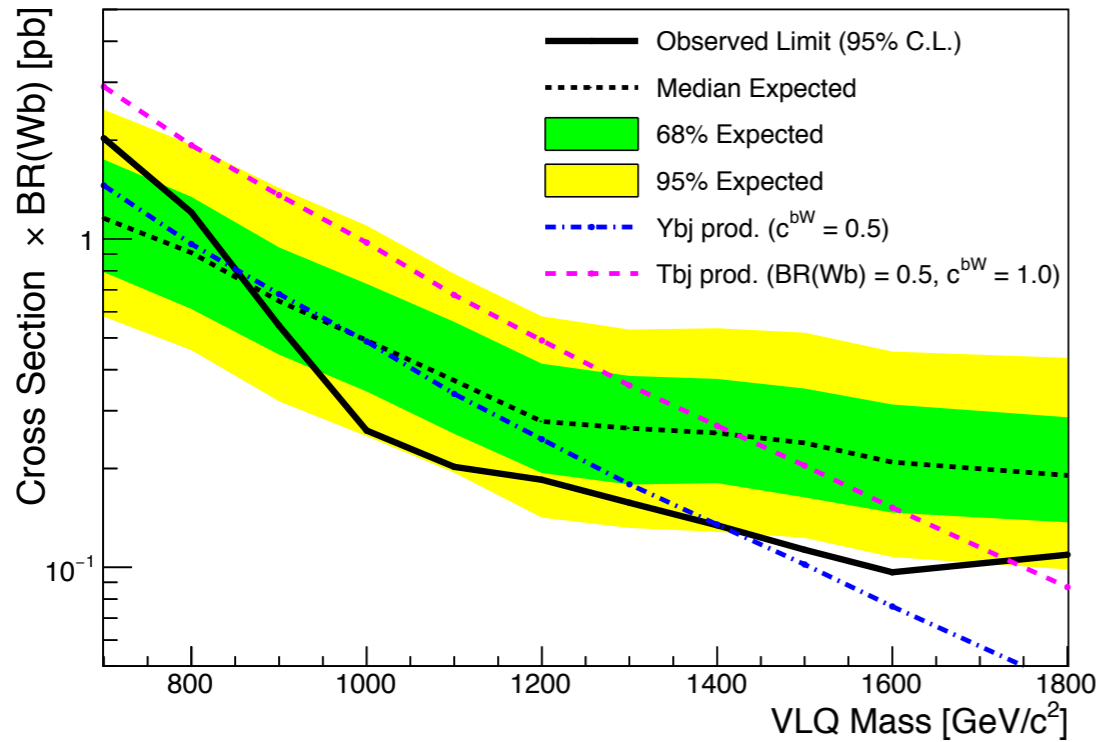
Measurement of the differential cross section for the production of a W ($\rightarrow \mu\nu$) boson in association with jets at $\sqrt{s} = 13$ TeV

CMS PAS SMP-15-006

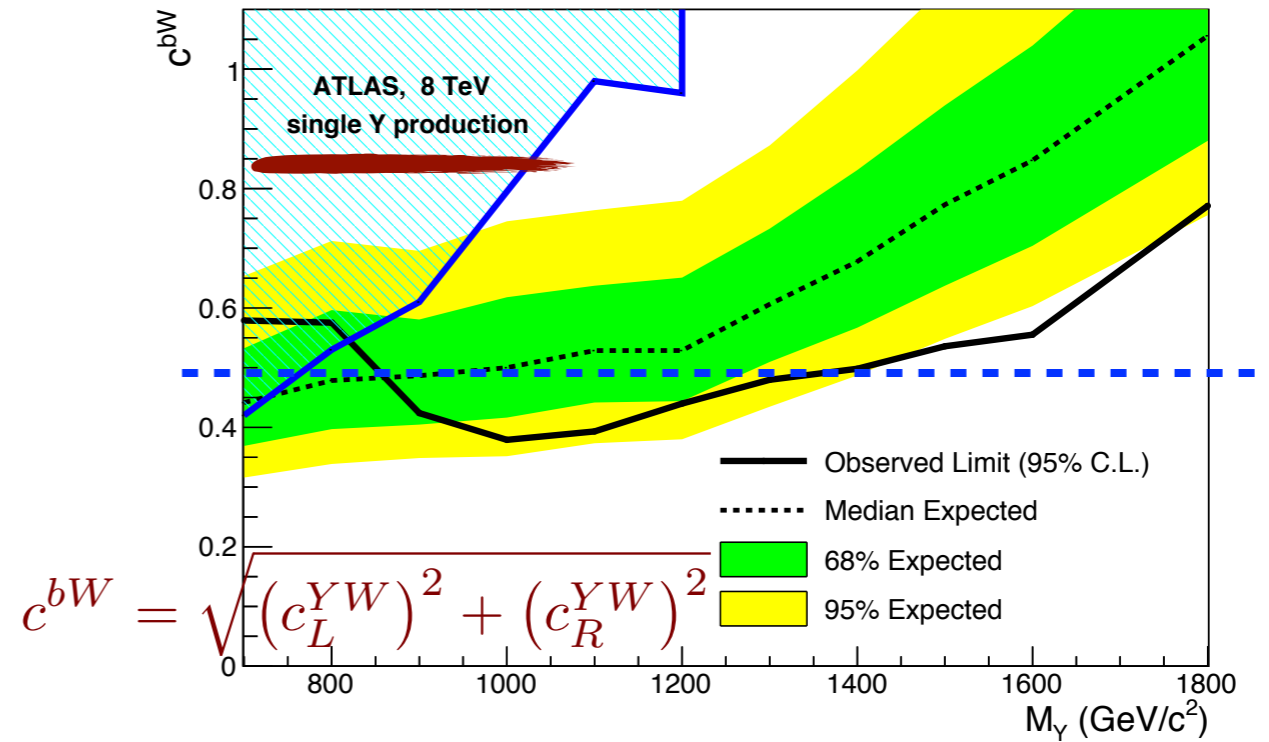
Single VLQ \rightarrow Wb

CMS PAS B2G-16-006 (07/16)

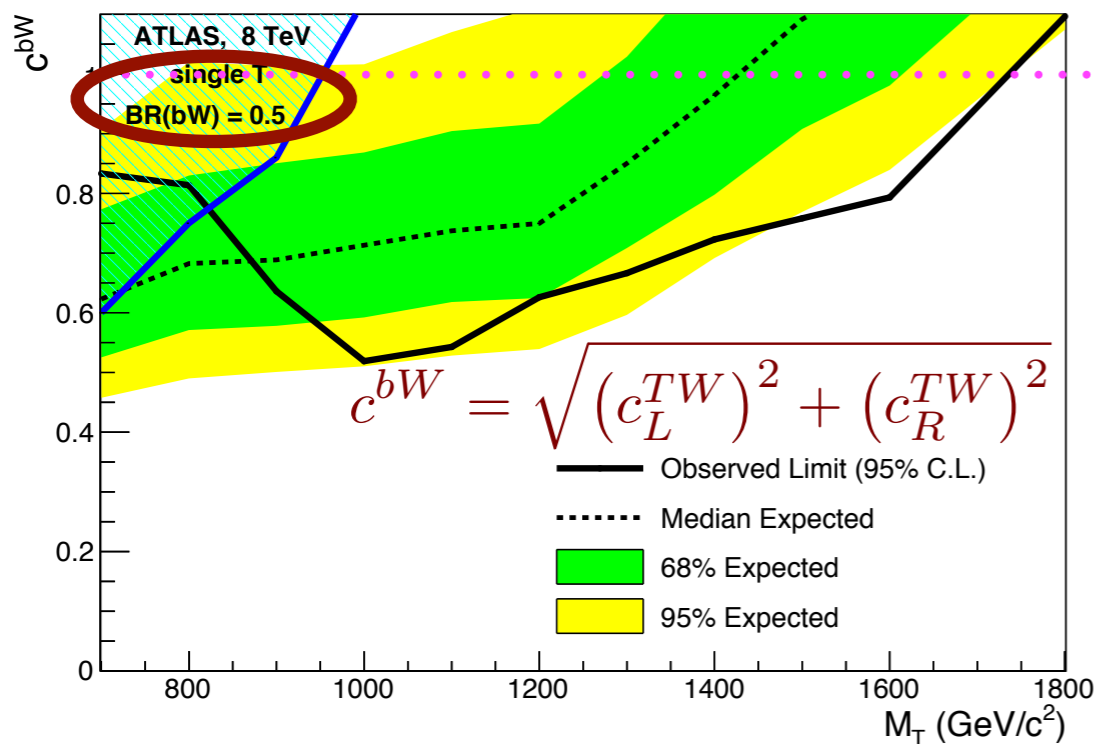
CMS Preliminary, 2.3 fb⁻¹ (13 TeV)



CMS Preliminary, 2.3 fb⁻¹ (13 TeV)



CMS Preliminary, 2.3 fb⁻¹ (13 TeV)



Interpretation

- mass limits for (large) benchmark couplings
- coupling limits for given BRs

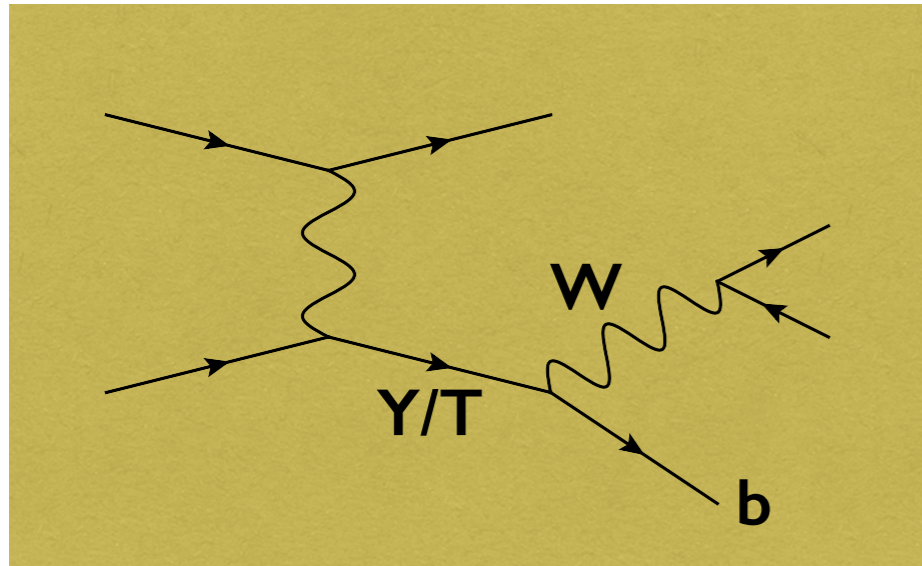
$$\sigma_{\text{sing}}(X\bar{t}) = [(c_L^{XV})^2 + (c_R^{XV})^2] \sigma_{\bar{V}t}(M_X) + c_L^{XV} c_R^{XV} \left(\frac{m_t}{M_X + m_t} \right) \sigma'_{\bar{V}t}(M_X),$$

$$\sigma_{\text{sing}}(X\bar{b}) = [(c_L^{XV})^2 + (c_R^{XV})^2] \sigma_{\bar{V}b}(M_X),$$

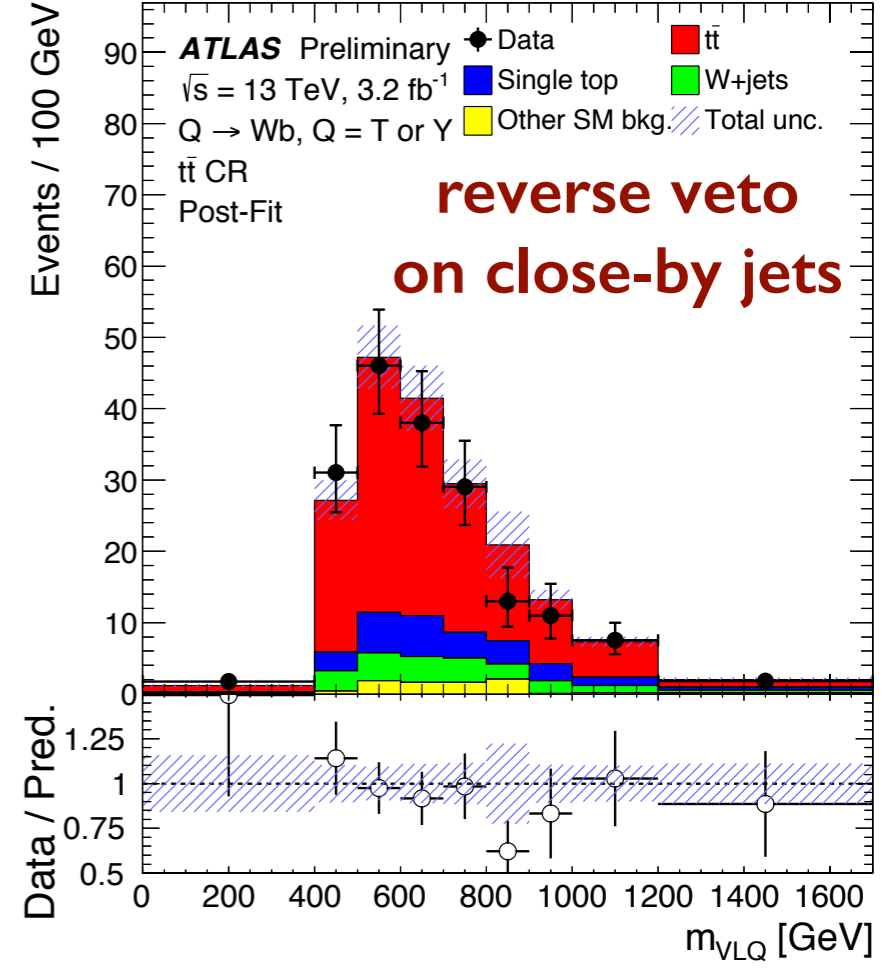
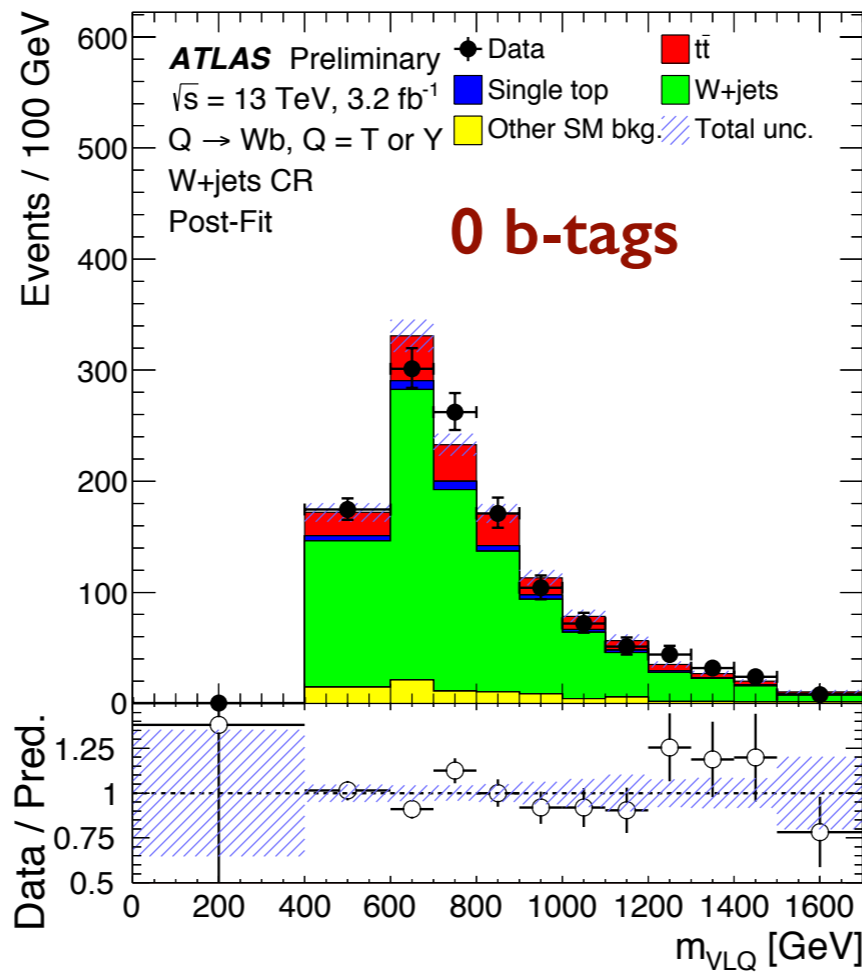
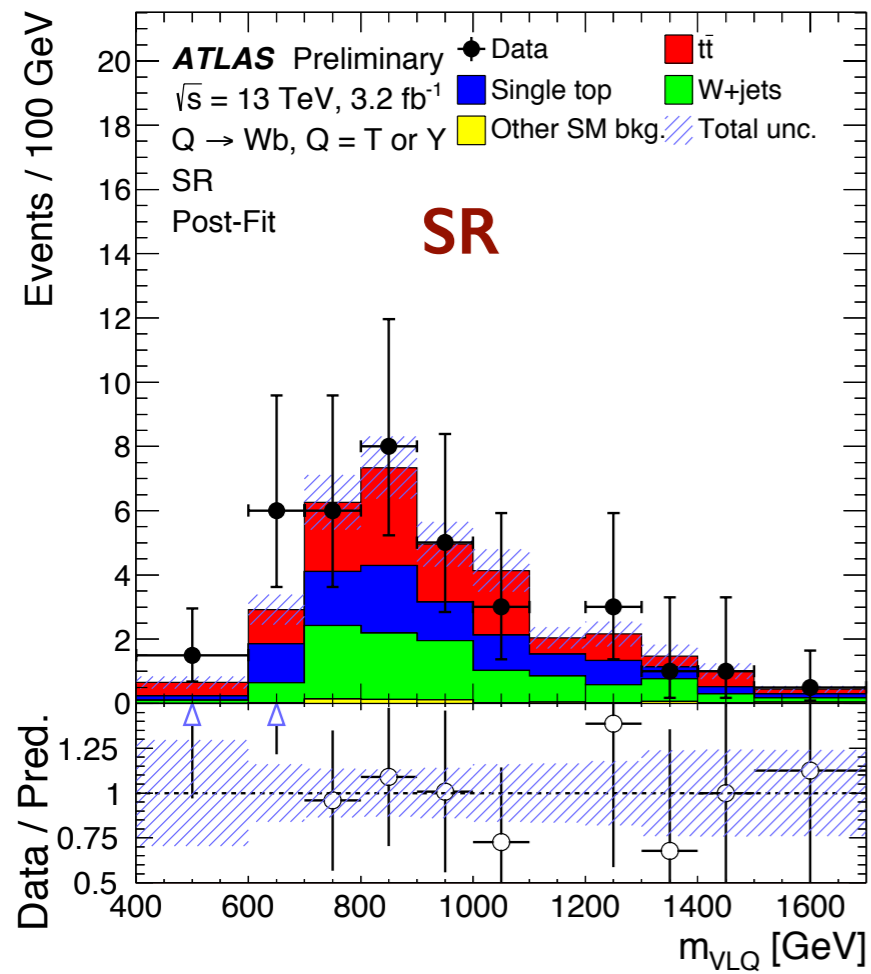
$$\sigma_{\text{sing}}(\bar{X}t) = [(c_L^{XV})^2 + (c_R^{XV})^2] \sigma_{\bar{V}t}(M_X) + c_L^{XV} c_R^{XV} \left(\frac{m_t}{M_X + m_t} \right) \sigma'_{\bar{V}t}(M_X),$$

$$\sigma_{\text{sing}}(\bar{X}b) = [(c_L^{XV})^2 + (c_R^{XV})^2] \sigma_{\bar{V}b}(M_X).$$

(Matsedonskyi, Panico, Wulzer, JHEP 12 (2014) 097)



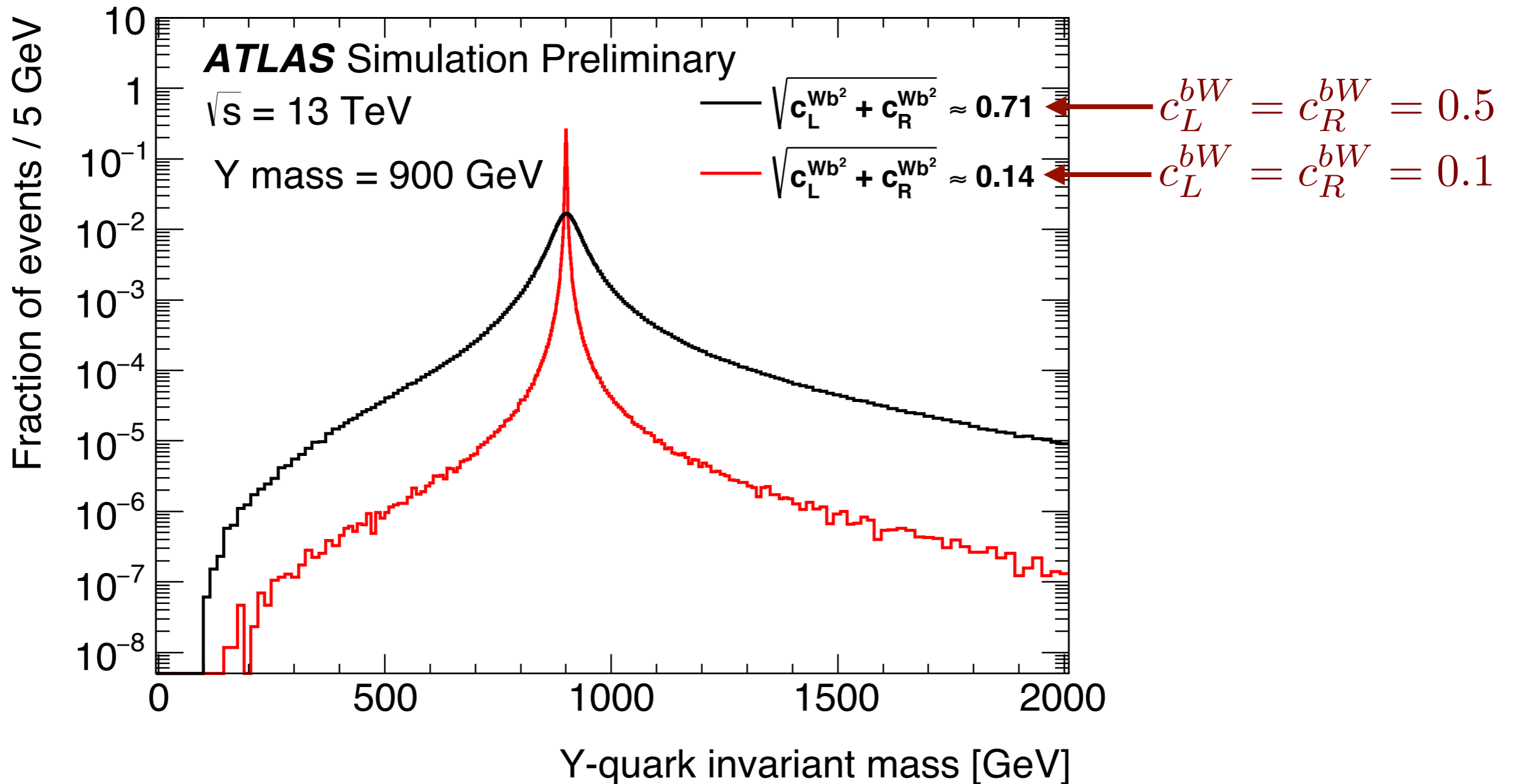
- very similar strategy as CMS
- + veto jets close/opposite leading jet (suppresses top background)
- simultaneous SR+CRs (top, W+jets) fit
- also here : W+jets needs correction (CR fit)



Single VLQ $\rightarrow Wb$

Width effects for different coupling values

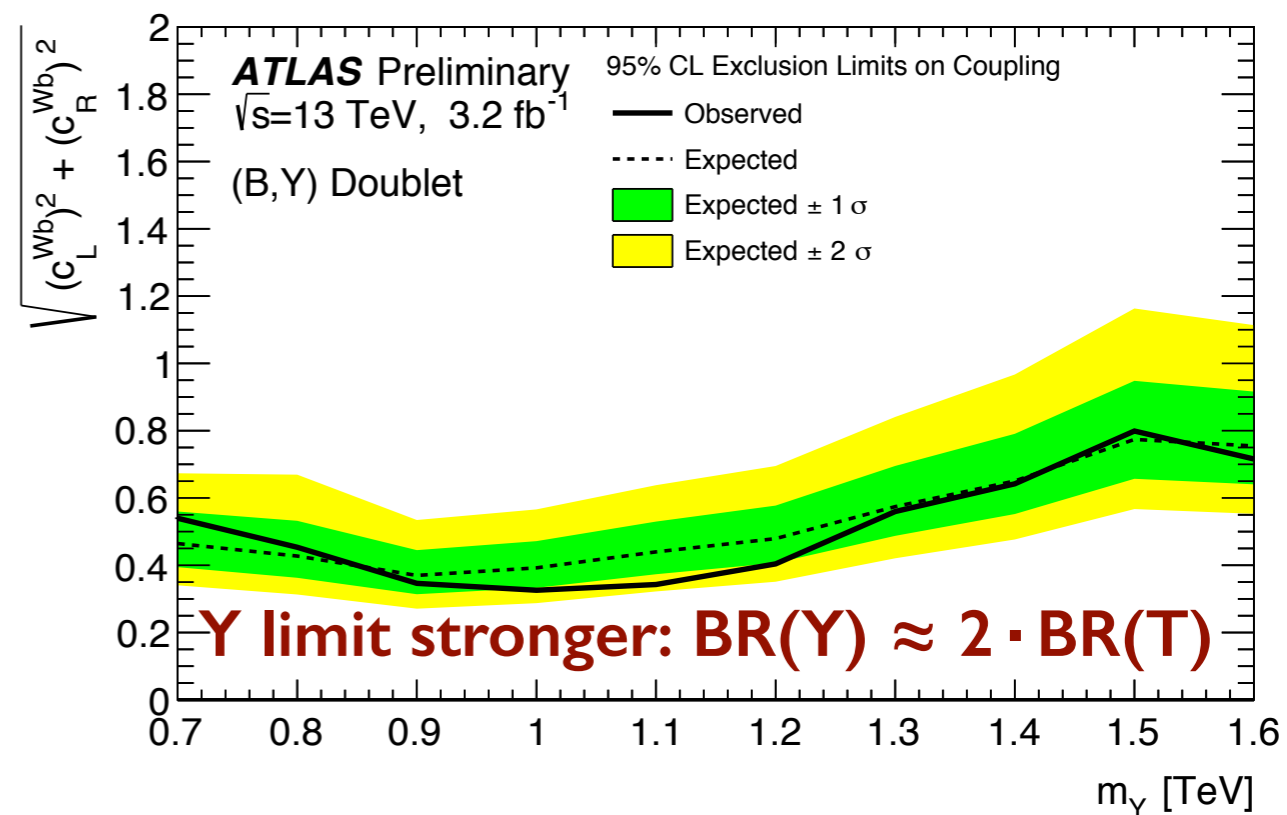
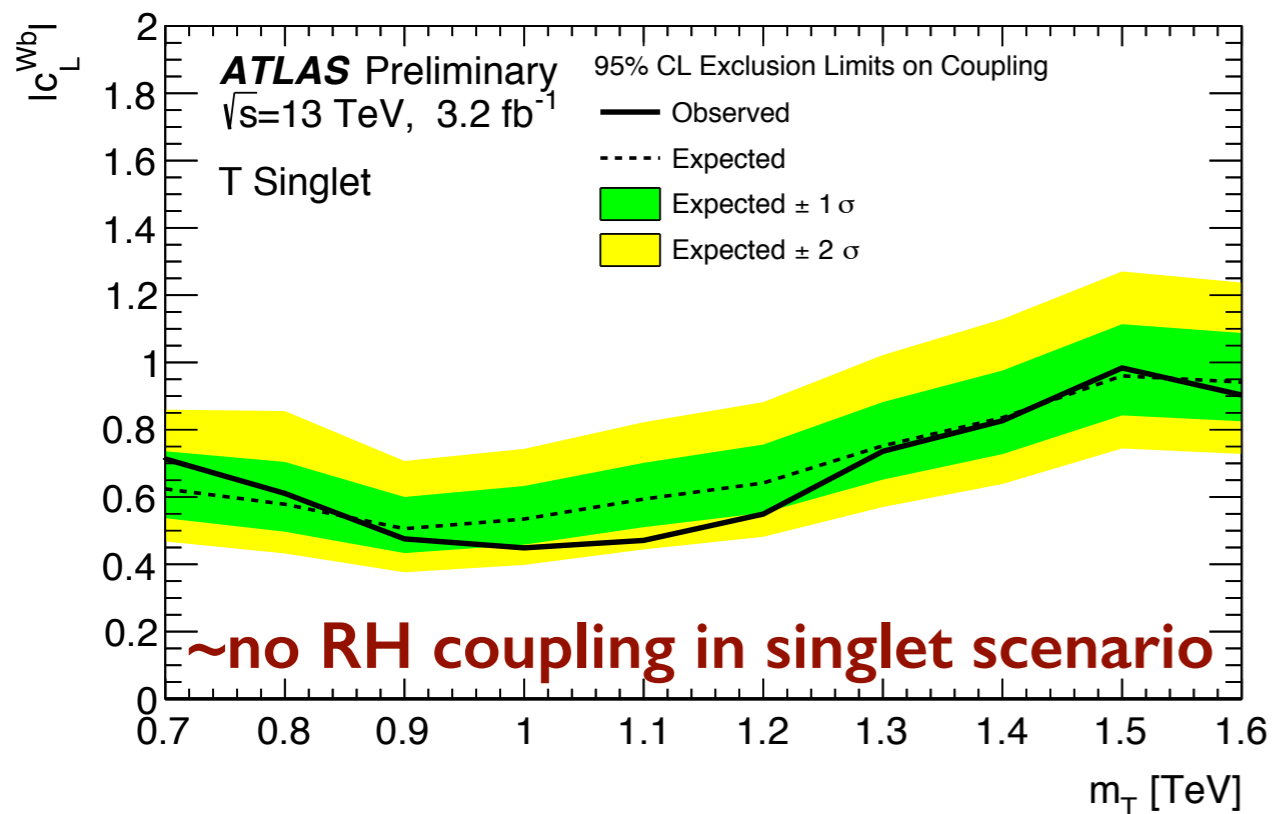
- non-negligible at truth level
- found to be small after reconstruction



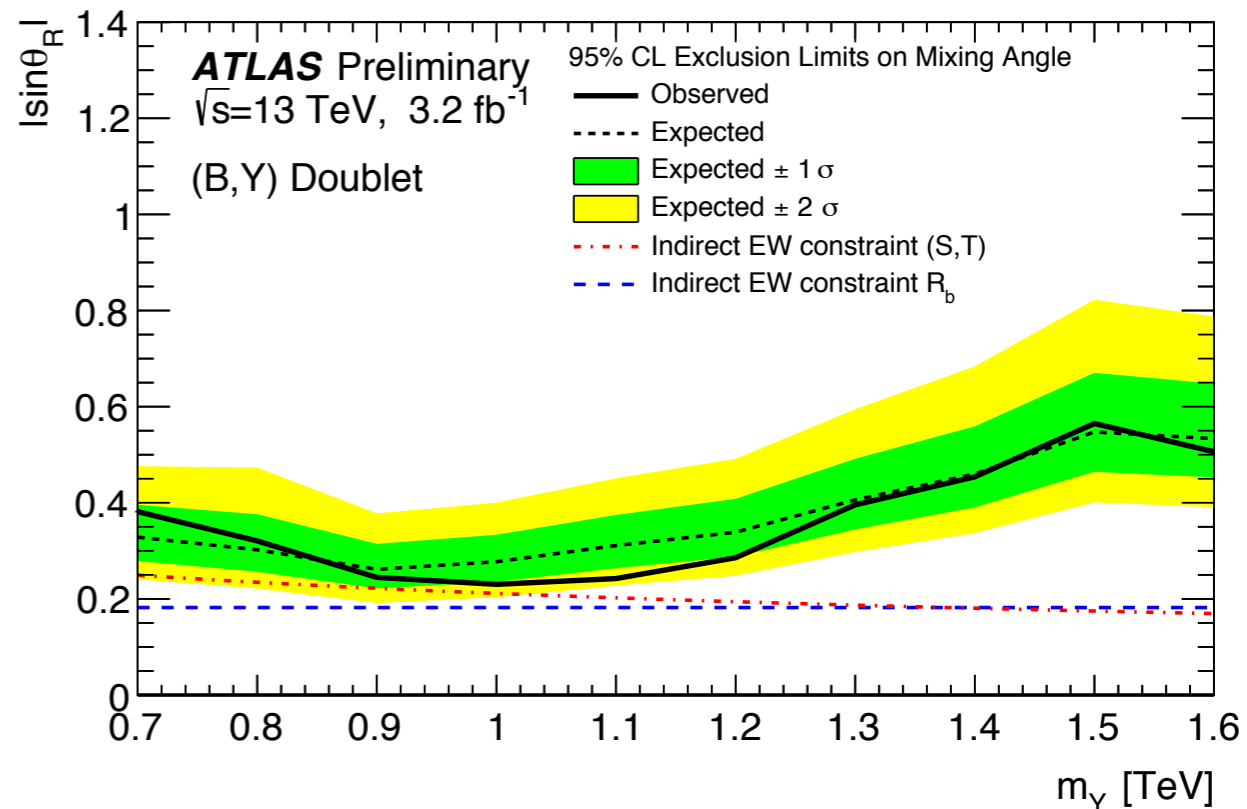
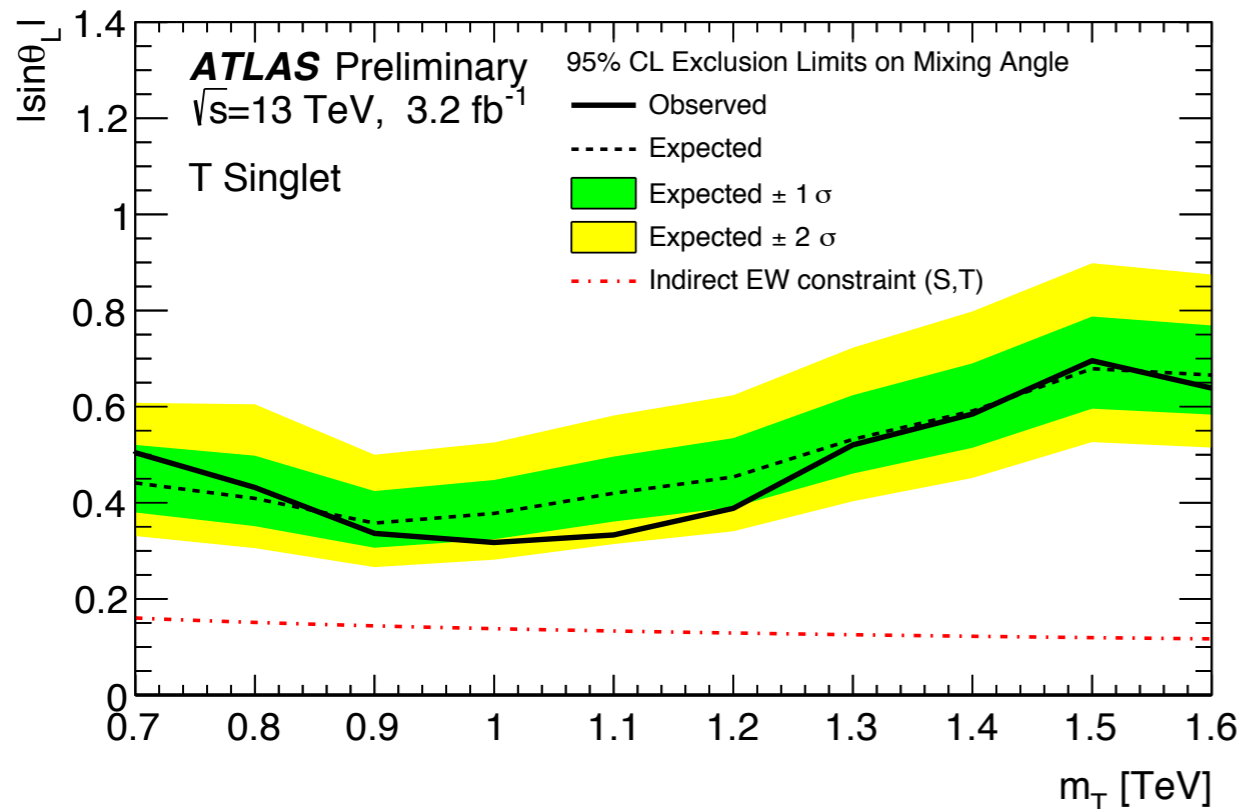


Single VLQ \rightarrow Wb

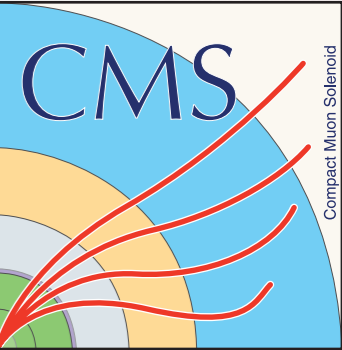
ATLAS-CONF-2016-072 (08/16)



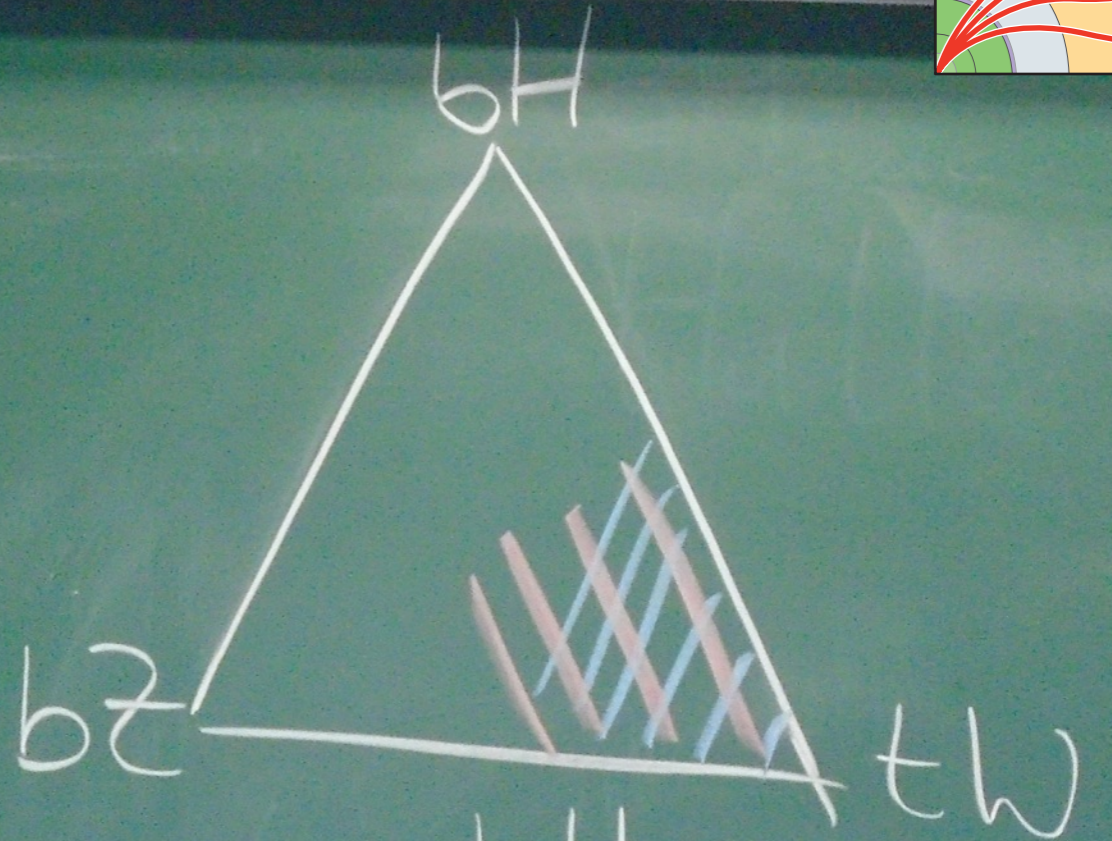
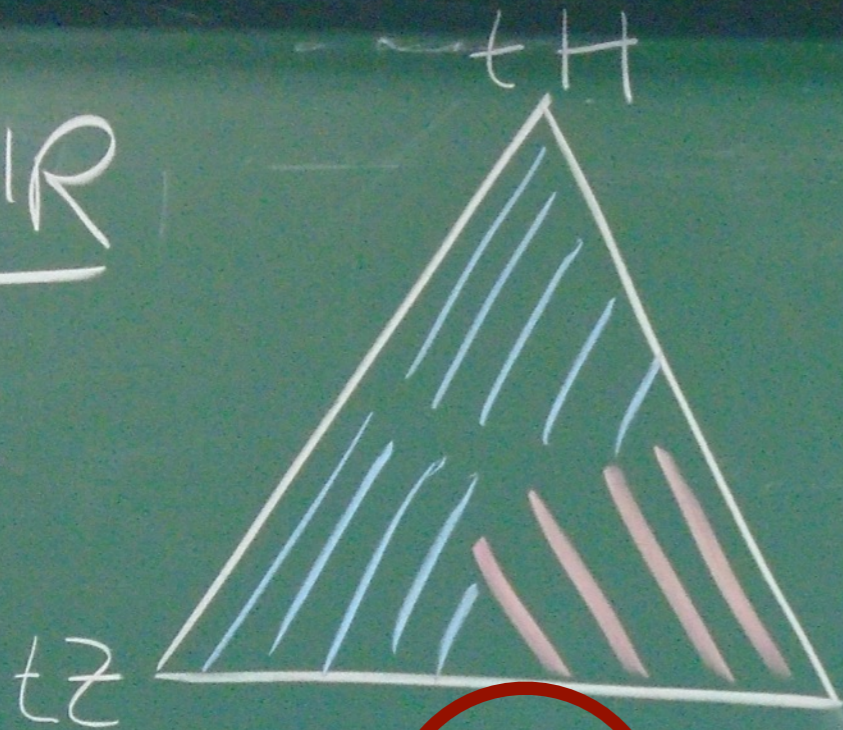
Also: limits on mixing angles $\theta_{L/R}$ — need to take into account also $BR(\theta_{L/R})$



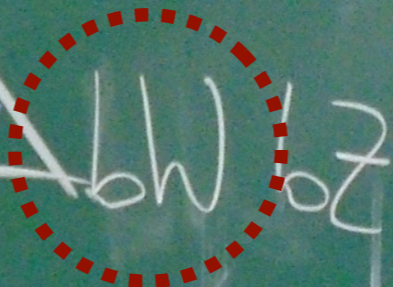
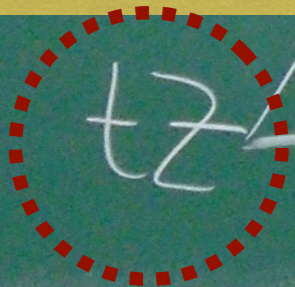
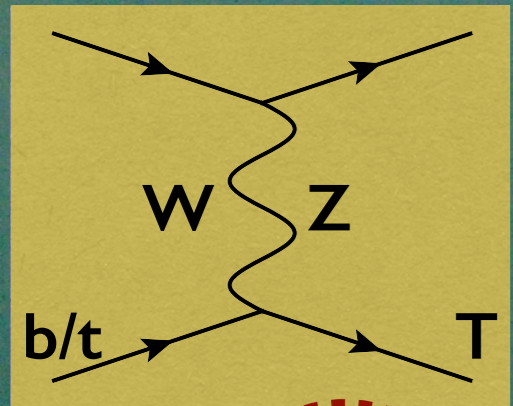
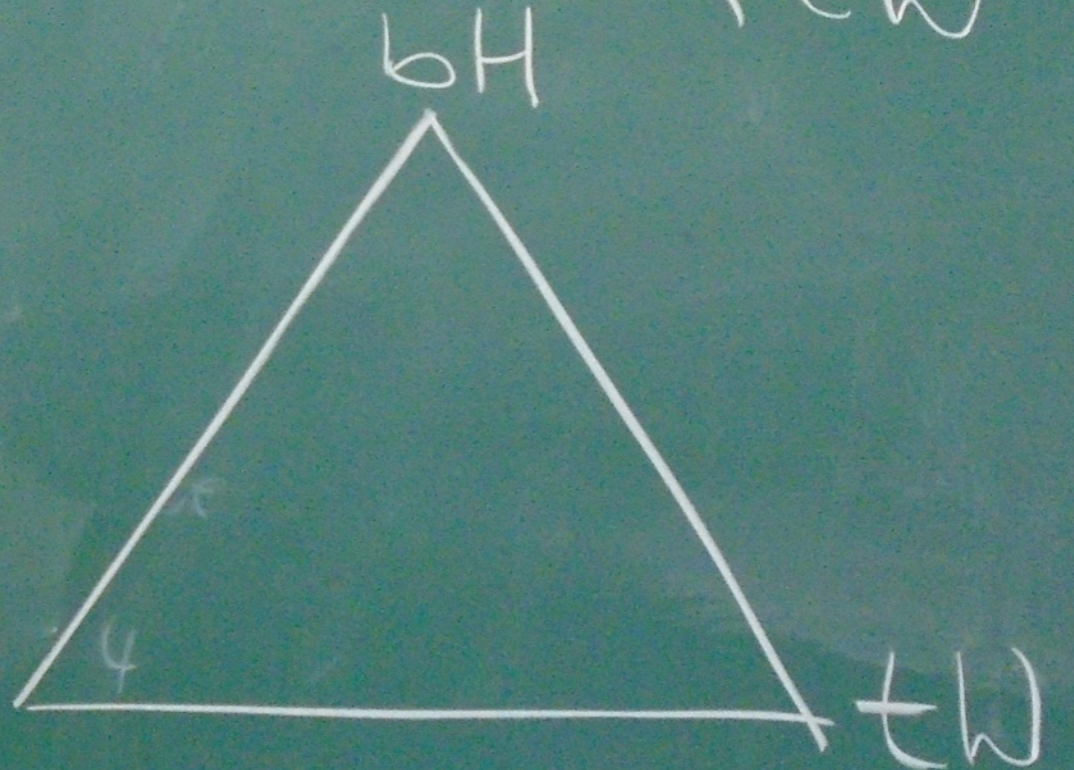
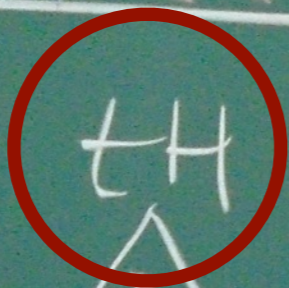
Single VLQ \rightarrow tH



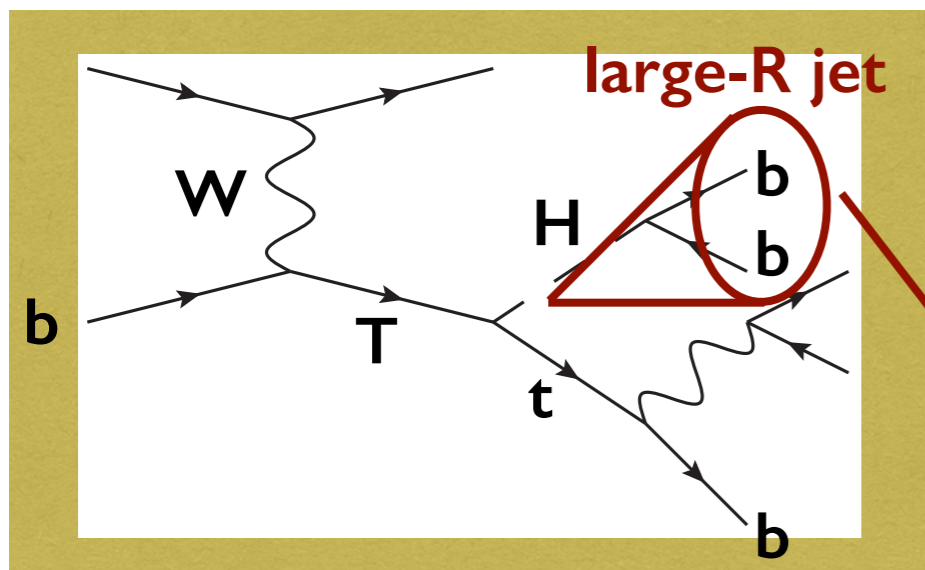
PAIR



SINGLE



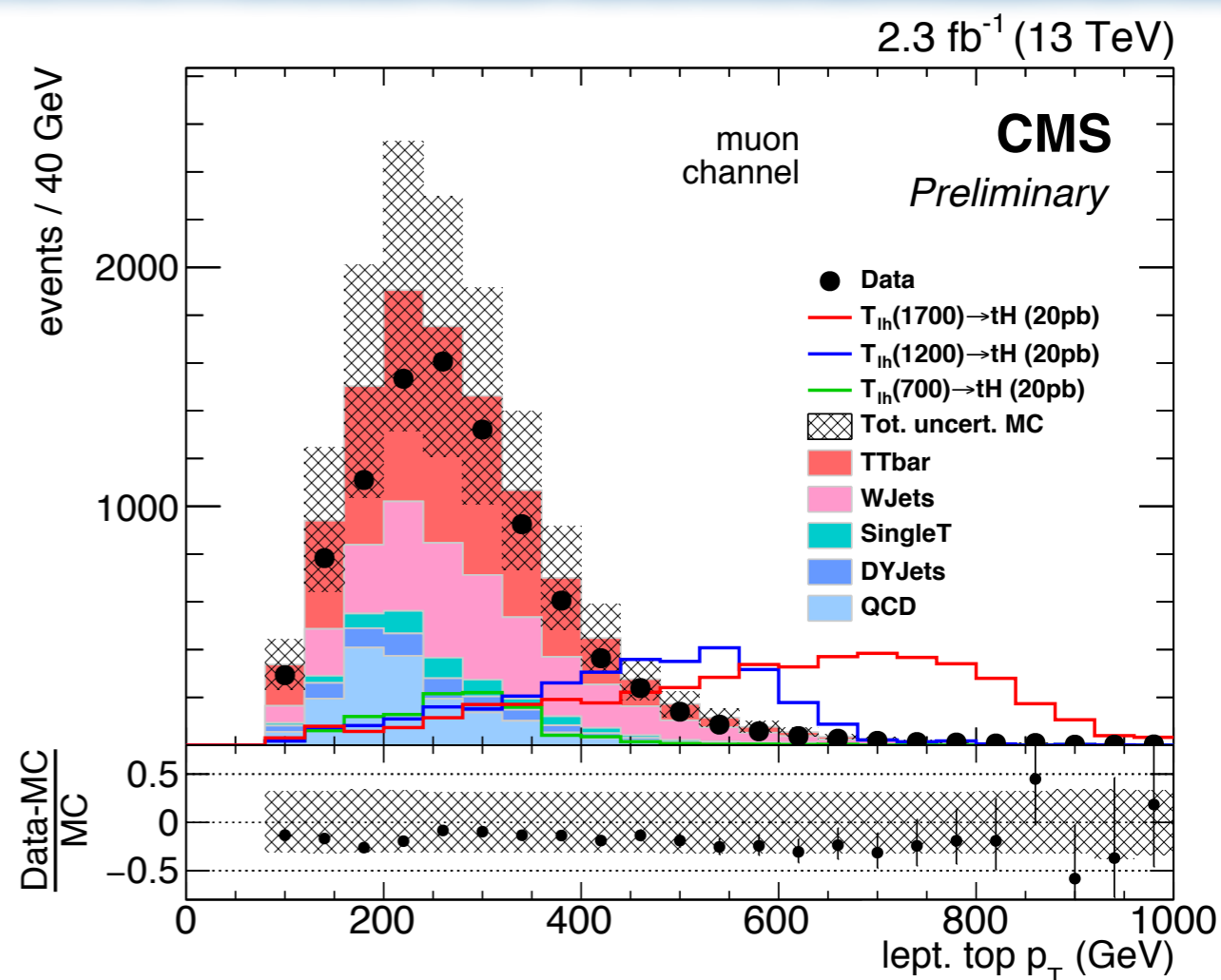
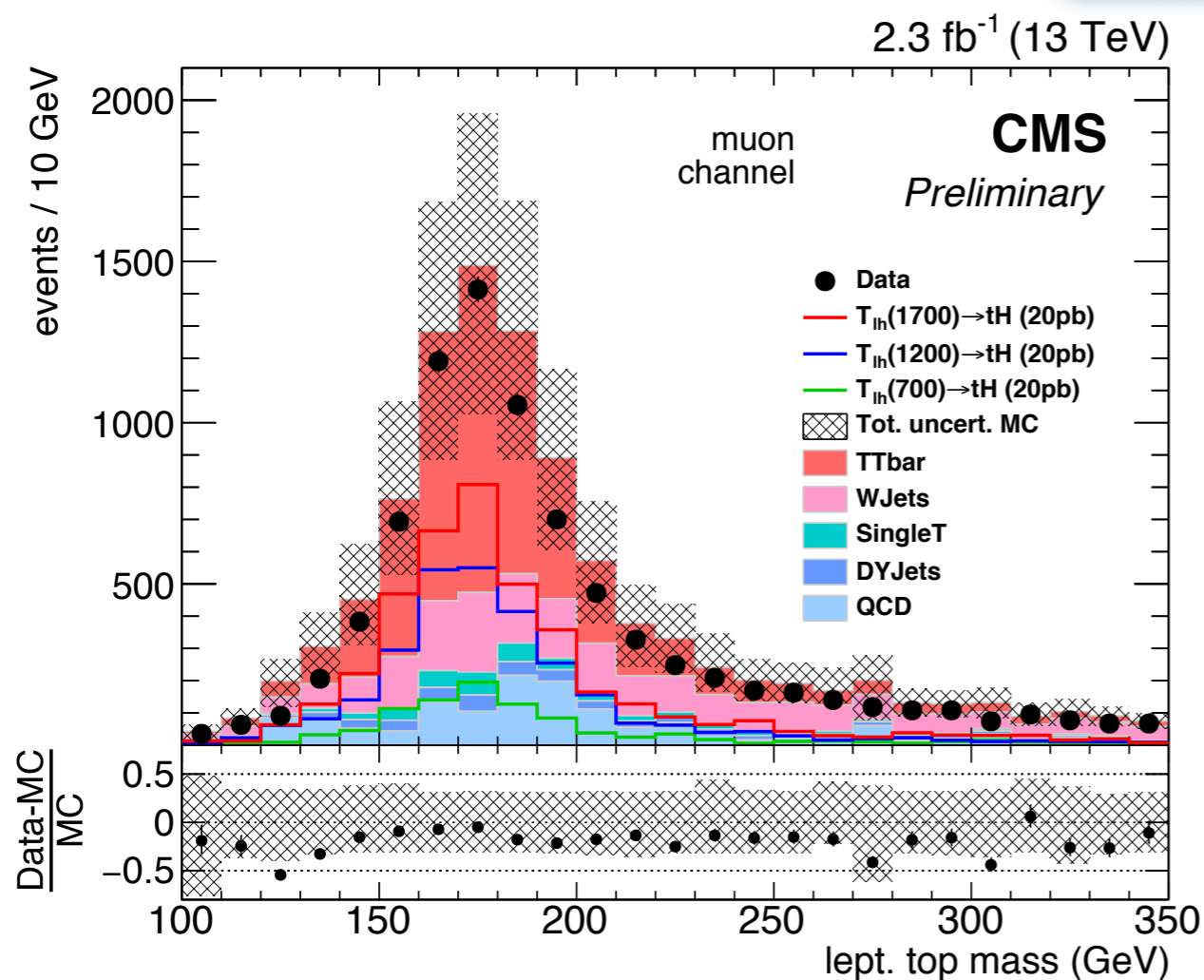
Single VLQ \rightarrow tH (leptonic top)

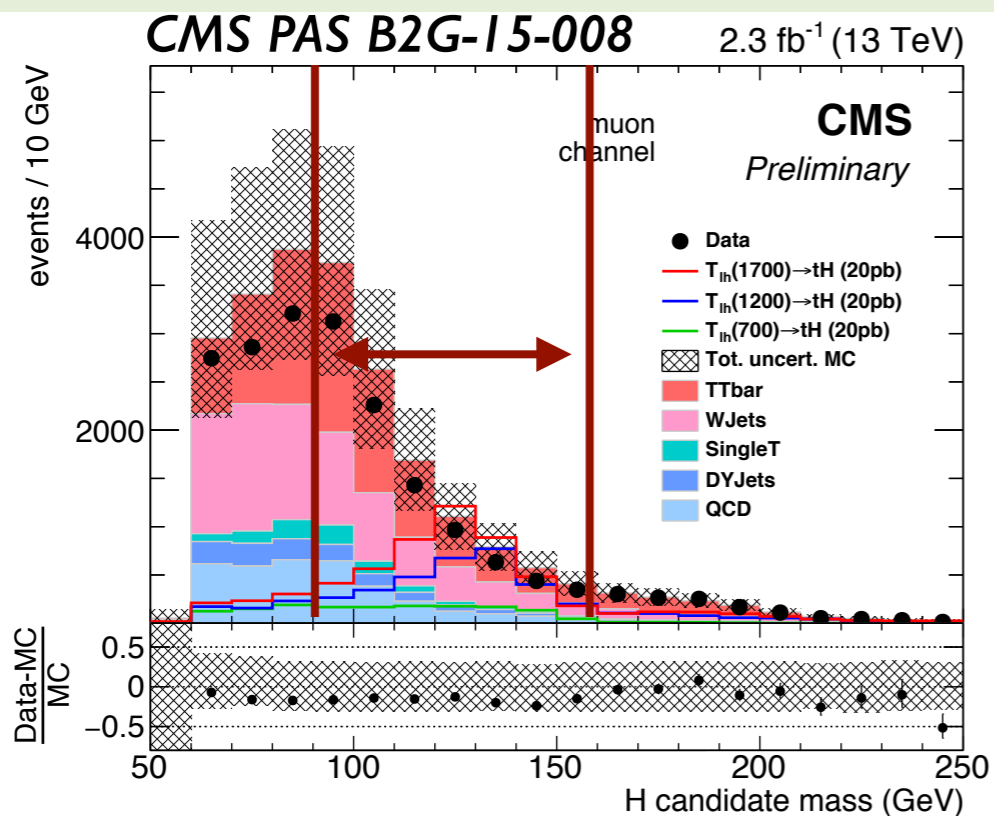


- e/ μ with isolation modified for high- p_T tops
- high- p_T central jets, high S_T , ≥ 1 forward jet
- kinematic top quark reconstruction :

$$\chi^2 = \left(\frac{M_{H,MC} - M_{H,rec}}{\sigma_{M_{H,MC}}} \right)^2 + \left(\frac{M_{t,MC} - M_{t,rec}}{\sigma_{M_{t,MC}}} \right)^2 + \left(\frac{\Delta R(t,H)_{MC} - \Delta R(t,H)_{rec}}{\sigma_{\Delta R,MC}} \right)^2$$

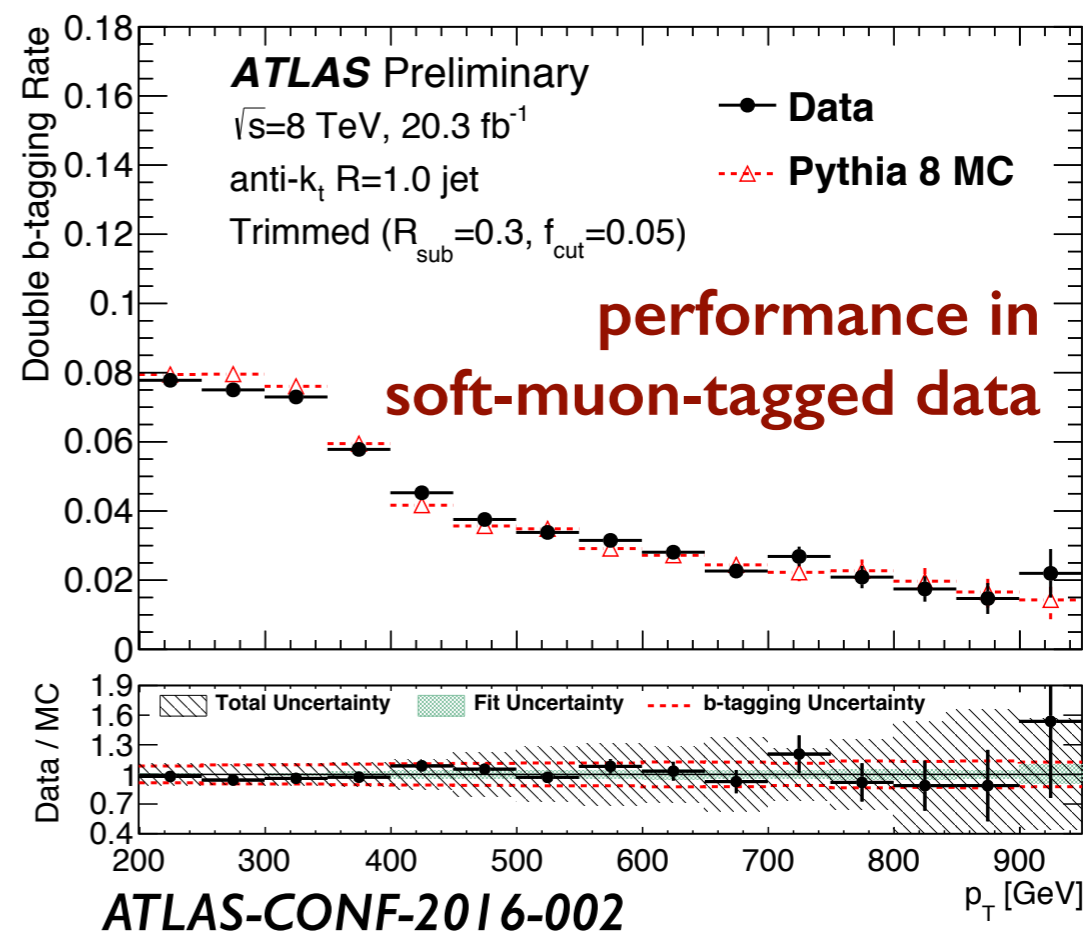
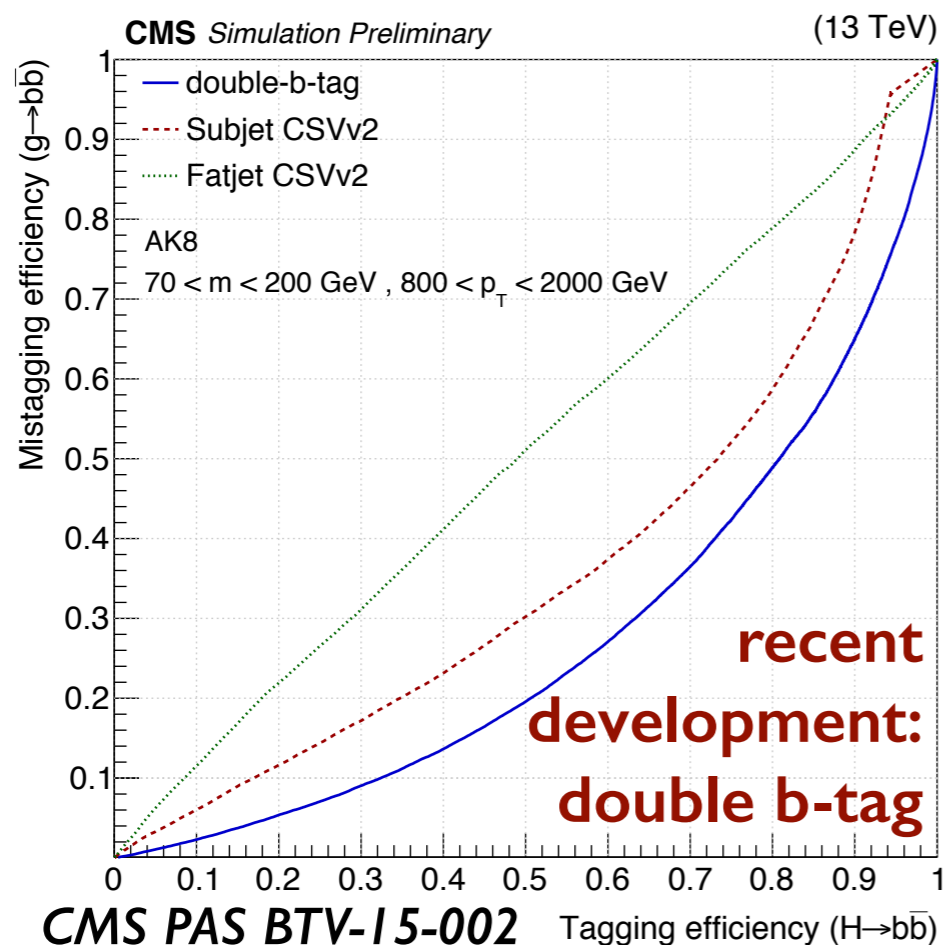
- ≥ 1 Higgs-tagged large-R jet (next slide)



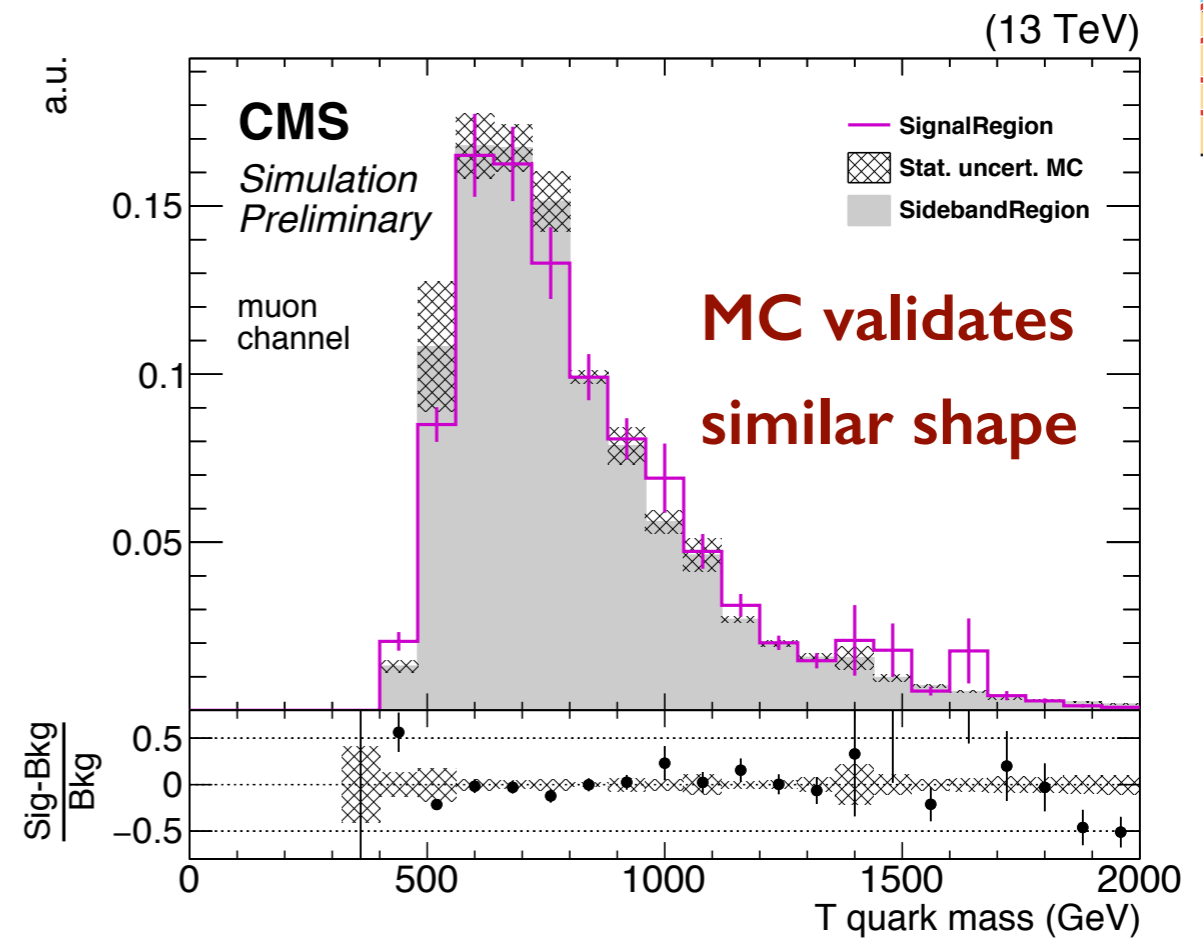
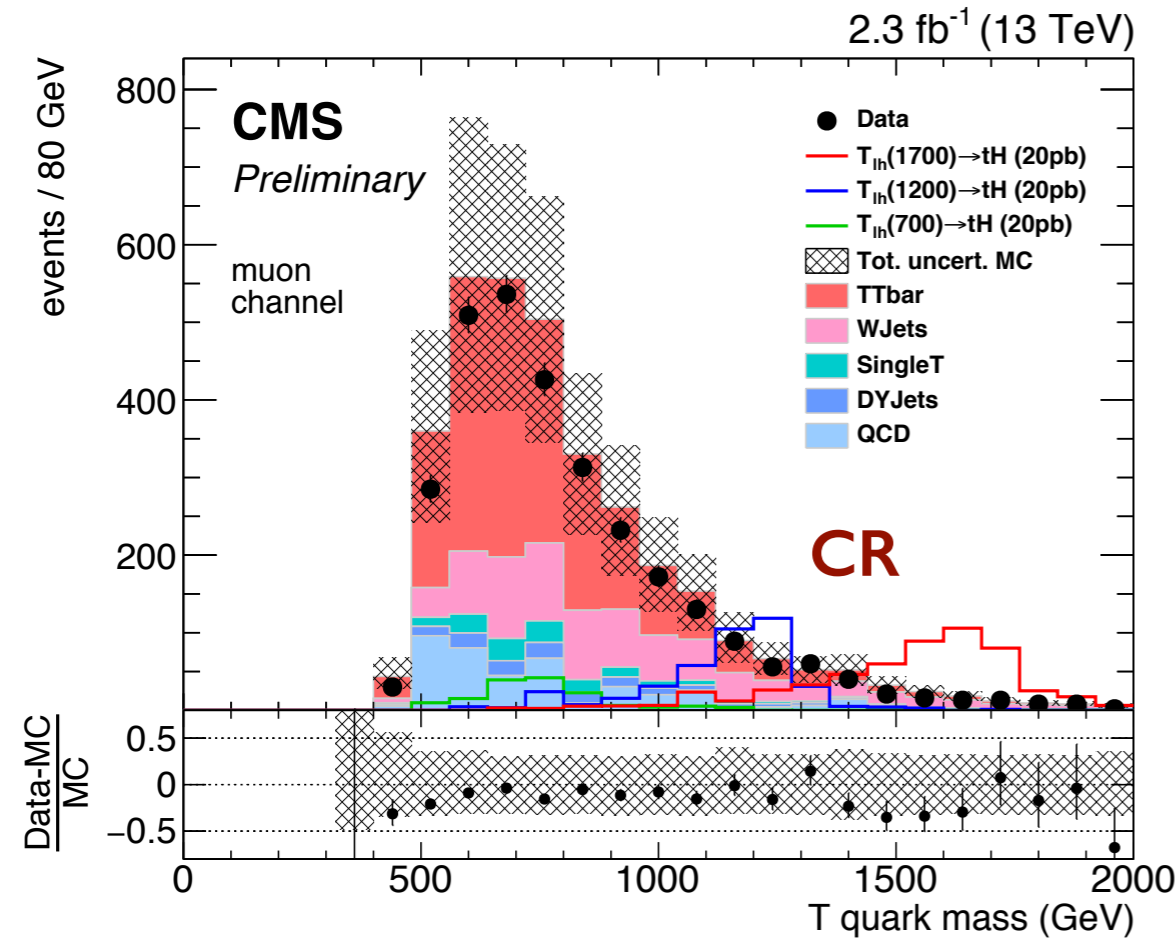


- jet mass: here — 90 GeV < m_{SD} < 160 GeV
- b-tagging is key:
here — subjet b-tagging

subjets
CMS PAS BTV-15-002

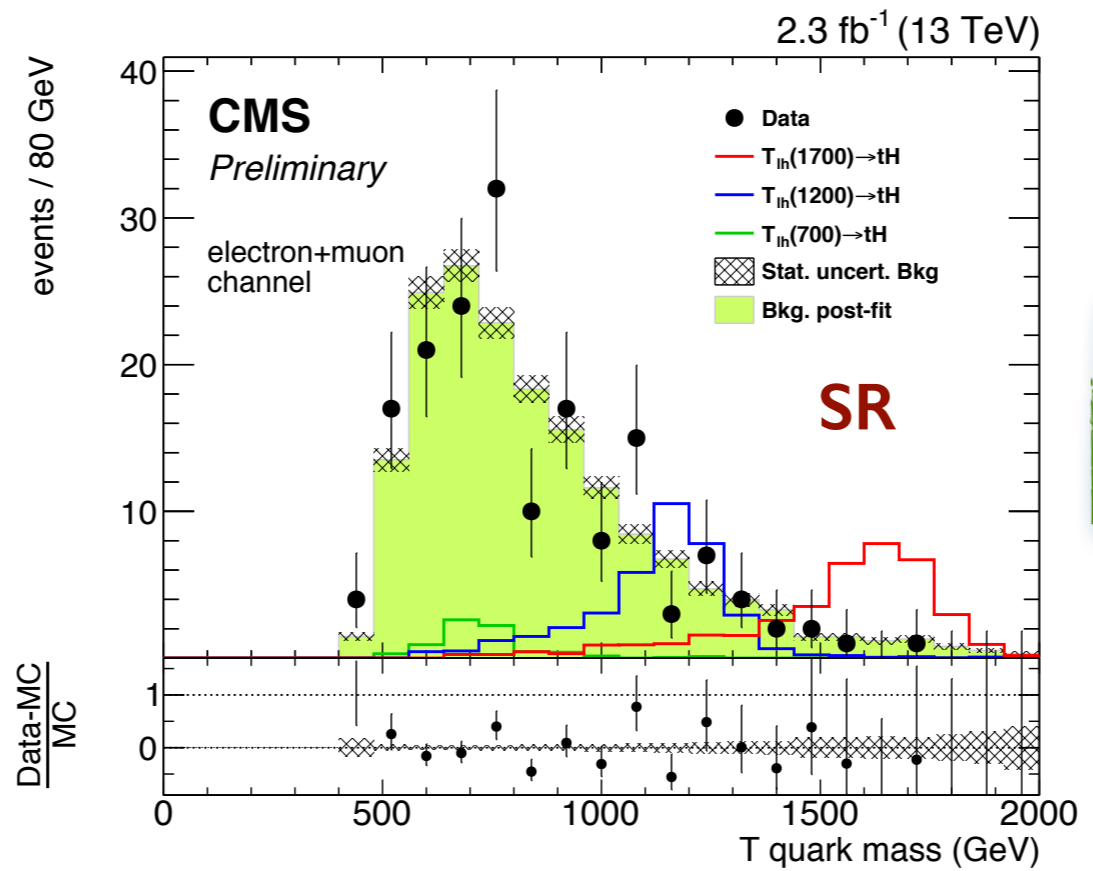


Single VLQ \rightarrow tH (leptonic top)



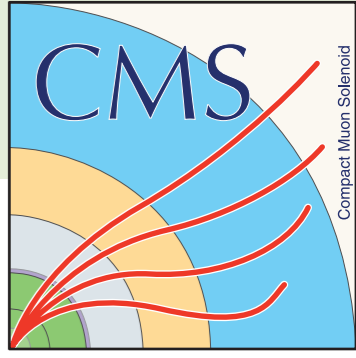
Full background shape taken from CR

- CR defined by
- no fwd. jet
 - 1 b-tag in H cand.
- ~ uncorrelated with m_T shape



Norm(bkg.) free in SR fit

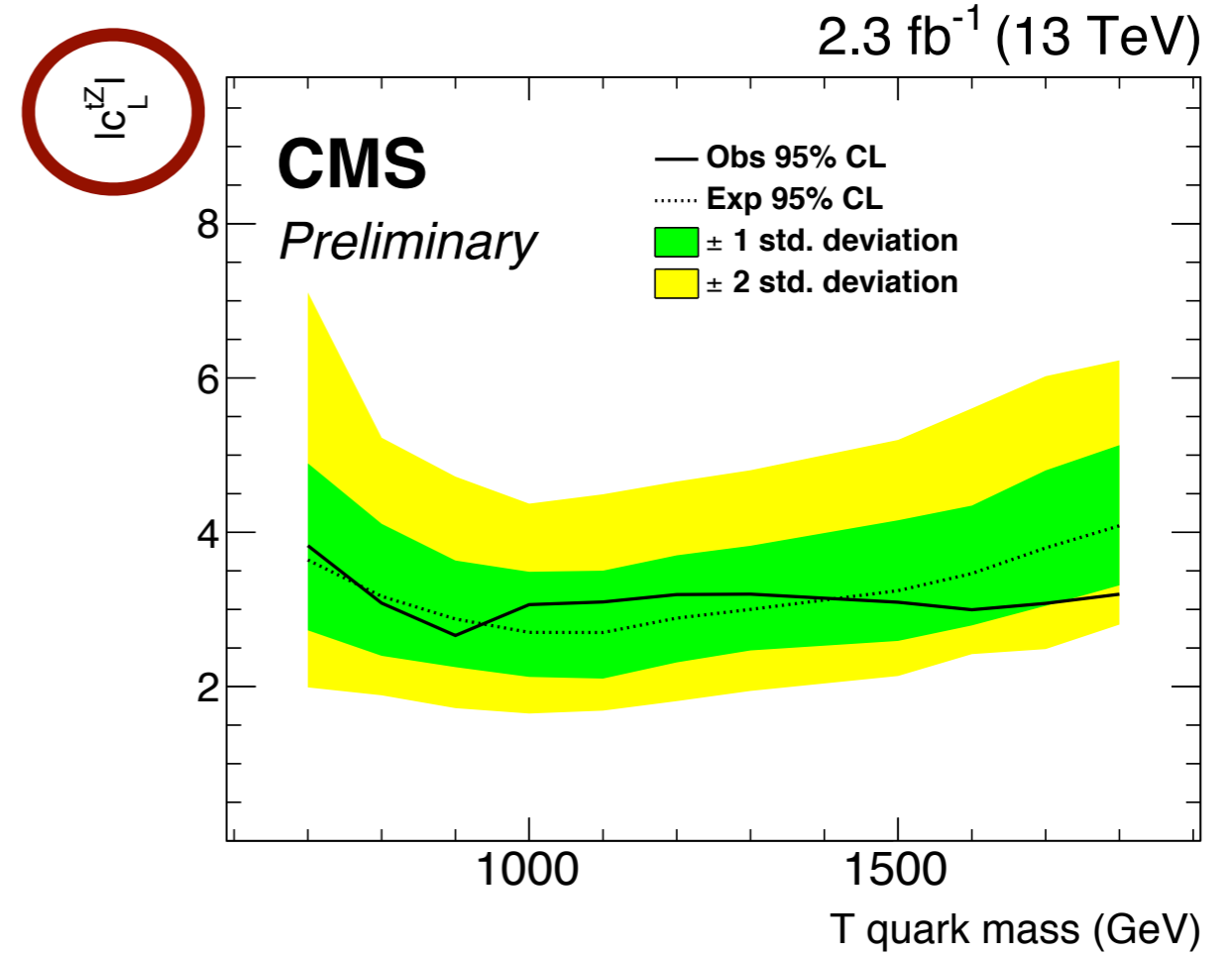
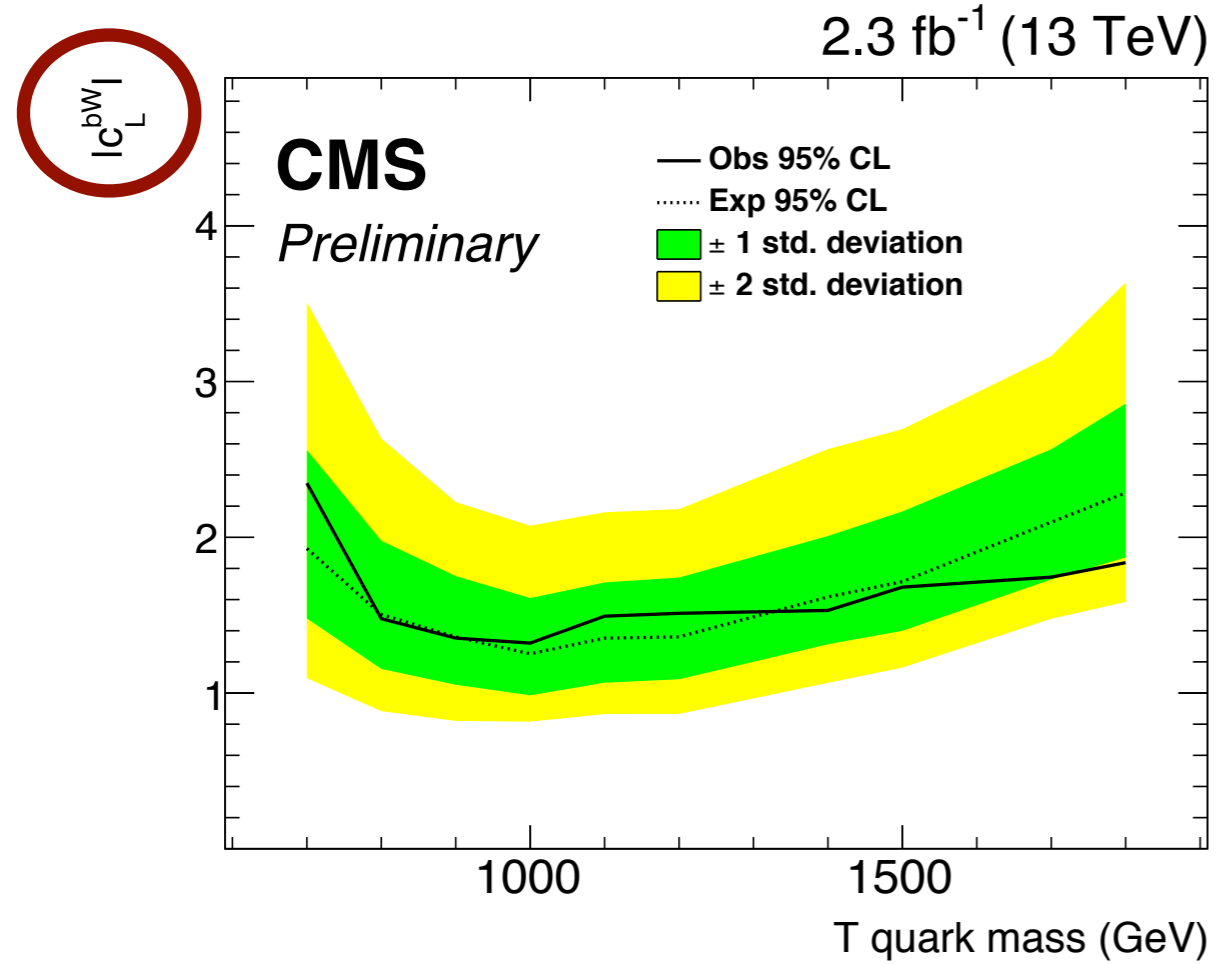
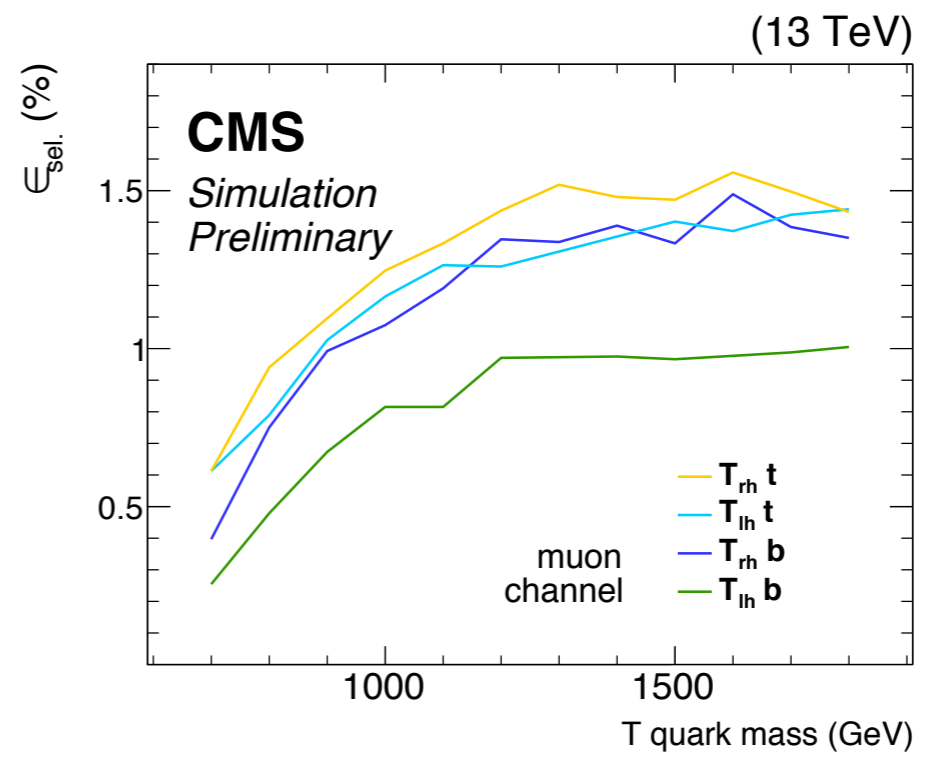
- 12% post-fit uncertainty

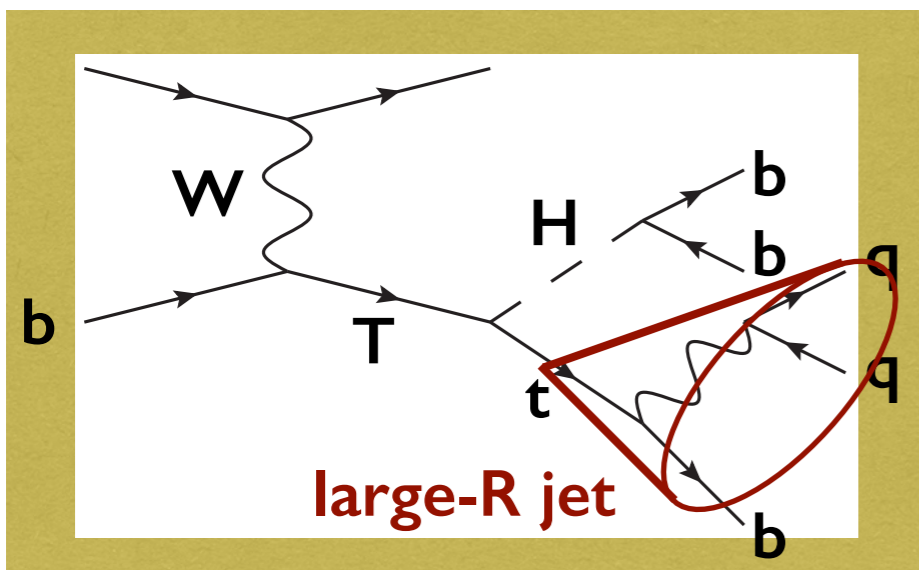


Benchmark interpretations

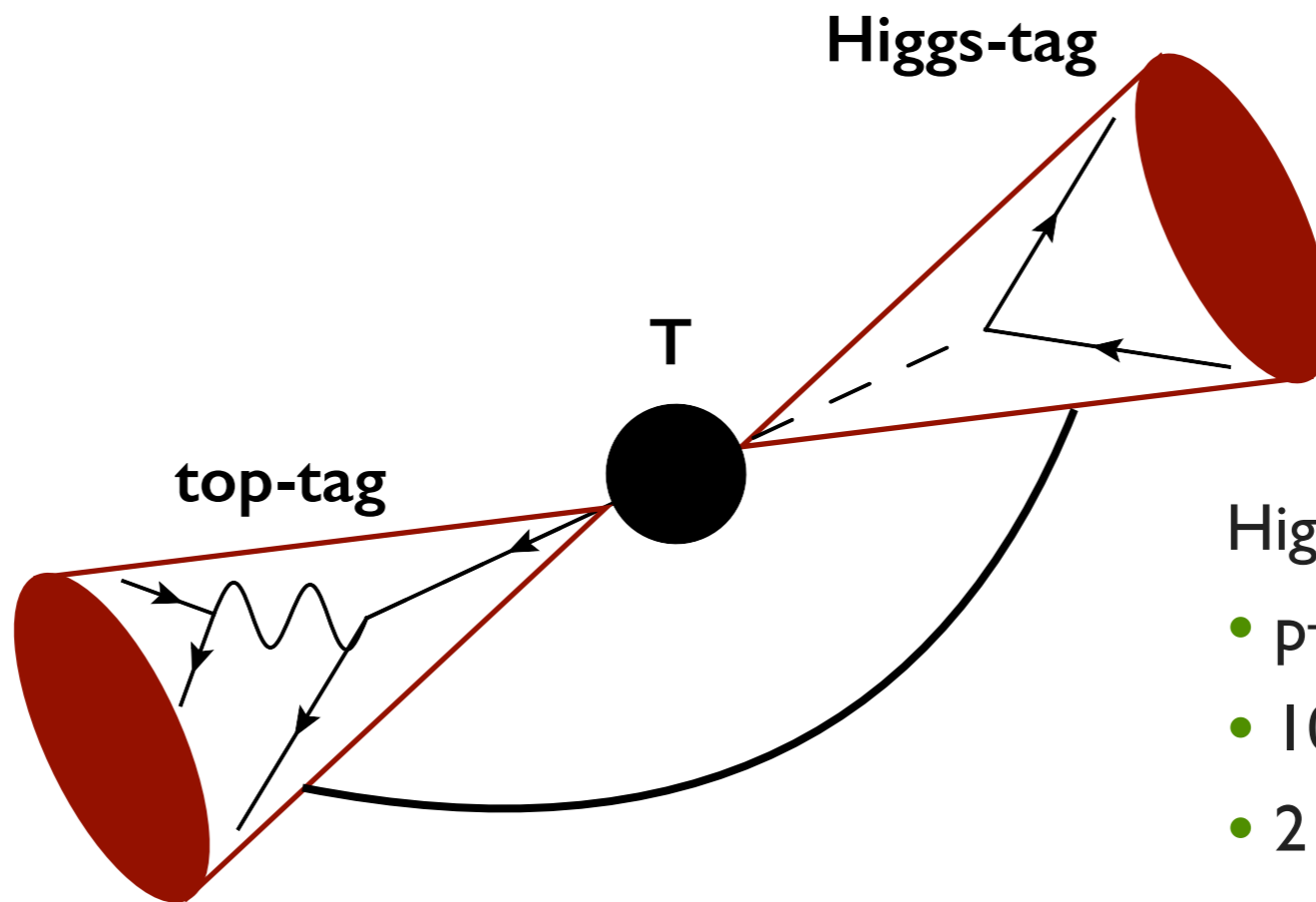
BR	Wb	Zt	Ht
Tbq	50%	25%	25%
Ttq	0%	50%	50%

ϵ depends on LH/RH and Tbq/Ttq





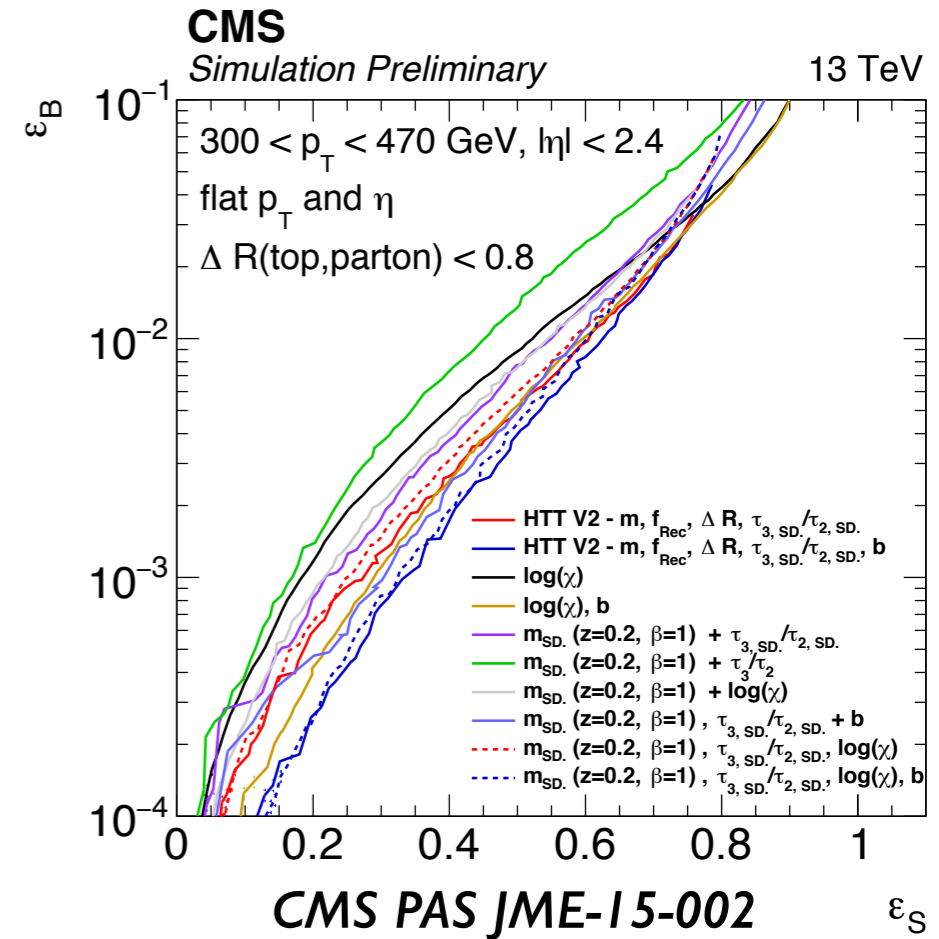
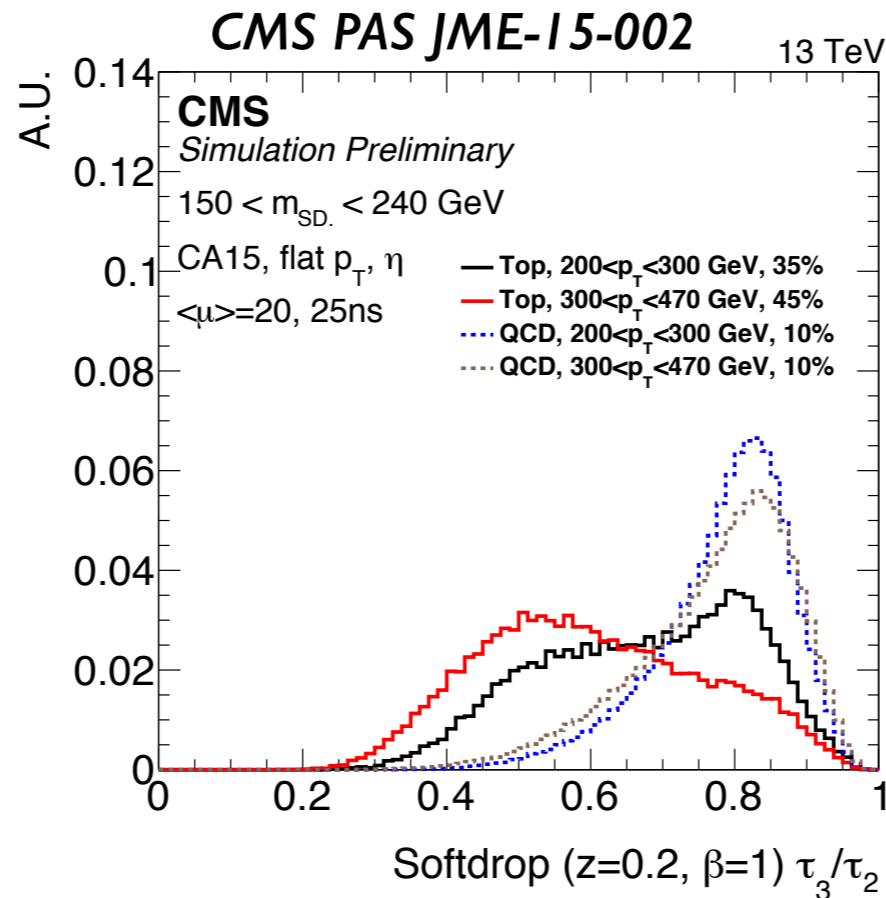
- fully hadronic analysis
- $\text{sum}(\text{jet activity}) \geq 800 \text{ GeV @ trigger}$
- ≥ 1 Higgs-tag & ≥ 1 top-tag with $\Delta R > 2.0$
- construct T candidate



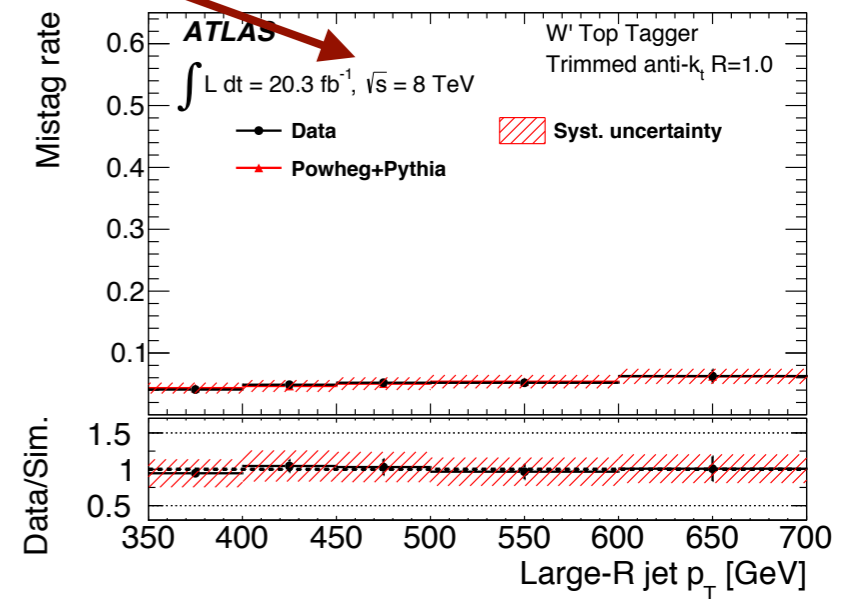
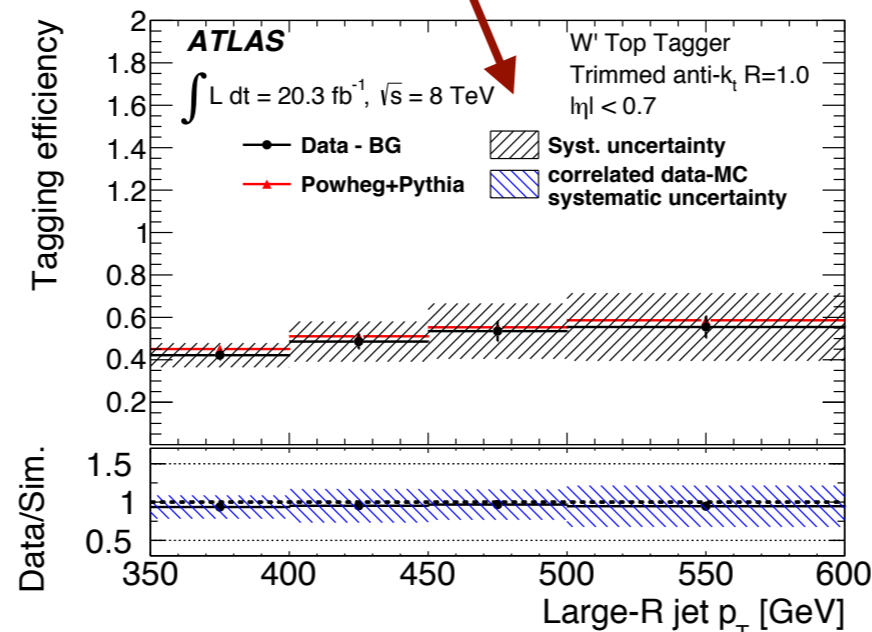
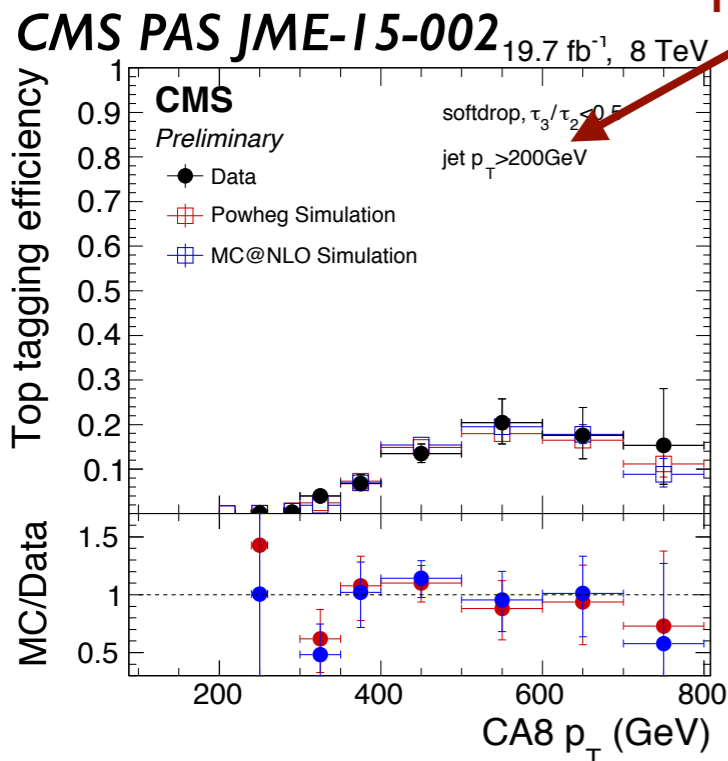
Higgs-tag here:

- $p_T > 300 \text{ GeV}$
- $105 < m_{\text{prun}} < 135 \text{ GeV}$
- 2 subjet b-tags
- $\tau_{21} < 0.6$

- top-tag here:
- $p_T > 400$ GeV
 - $\tau_{32} < 0.54$
 - 3- vs. 2-prong
 - 1 subjet b-tags



Top-tagging thoroughly validated with 8 TeV data

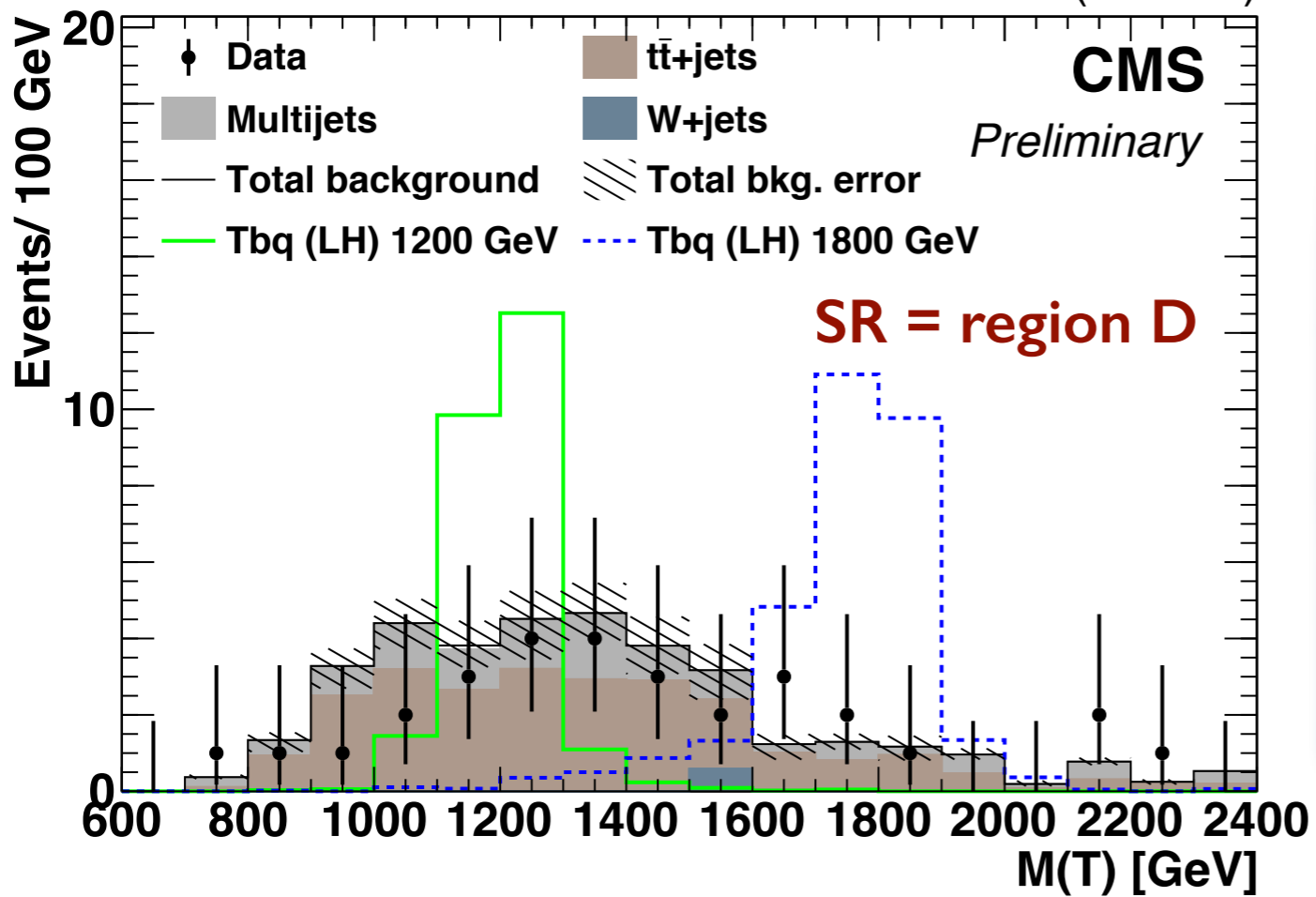


CMS PAS B2G-16-005 (06/16) **Single VLQ \rightarrow tH (hadronic top)**

QCD multijet background
 ABCD method : $N_D = N_B \cdot \frac{N_C}{N_A}$

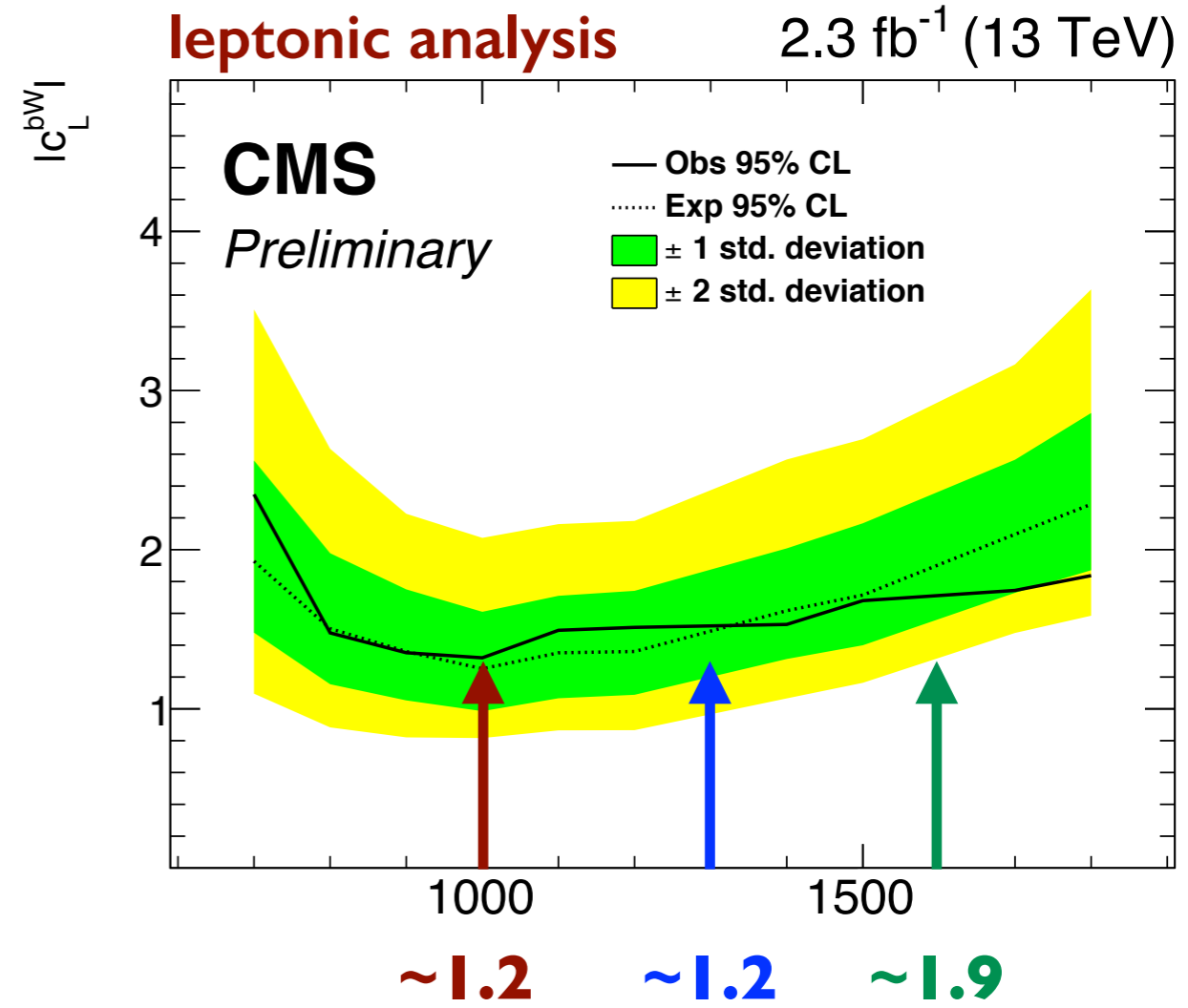
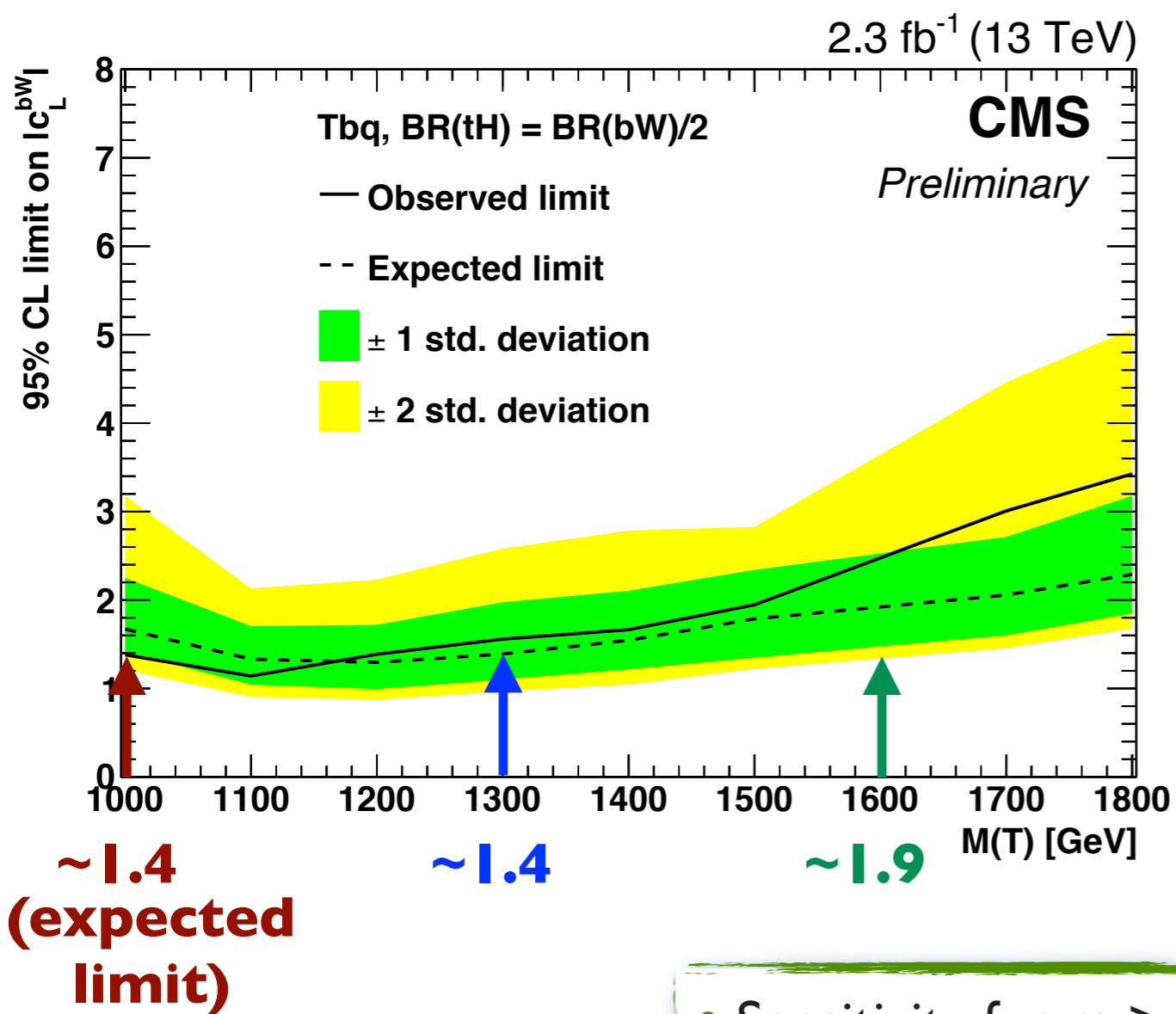
QCD percentage	no top-tag	top-tag
no H-tag	A ~100%	B ~80%
H-tag	C ~70%	D = SR ~30%

2.3 fb⁻¹ (13 TeV)



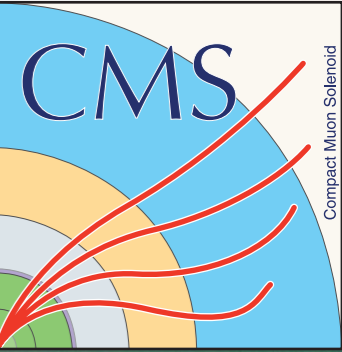
- QCD syst. from bkg. subtraction
 - (anti-)correlated in stat. analysis
- significant systematics
 - Higgs-tag N-subjettiness 12.5%
 - jet mass 10%
 - top-tagging 15-30%

CMS PAS B2G-16-005 (06/16) Single VLQ \rightarrow tH (hadronic top)

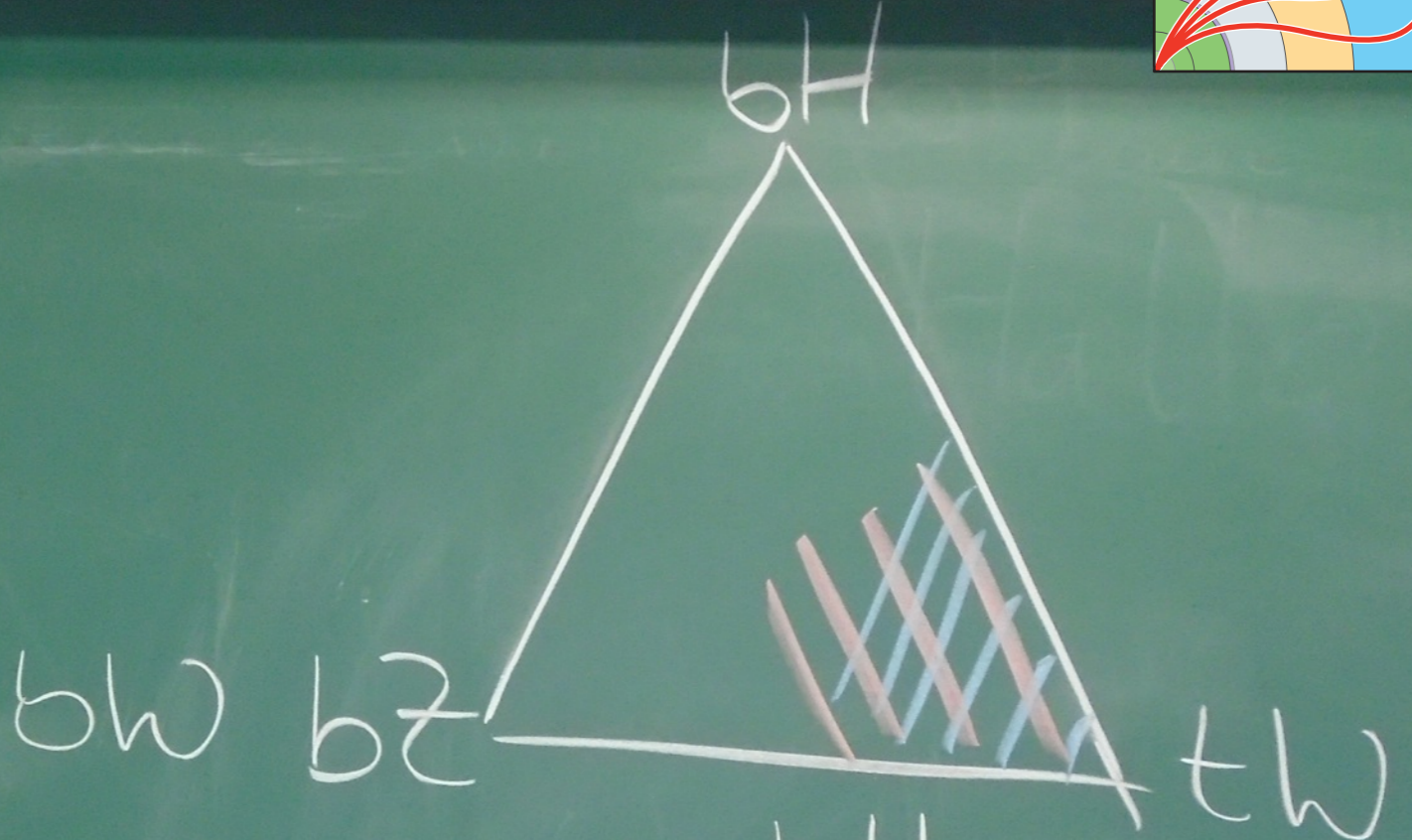
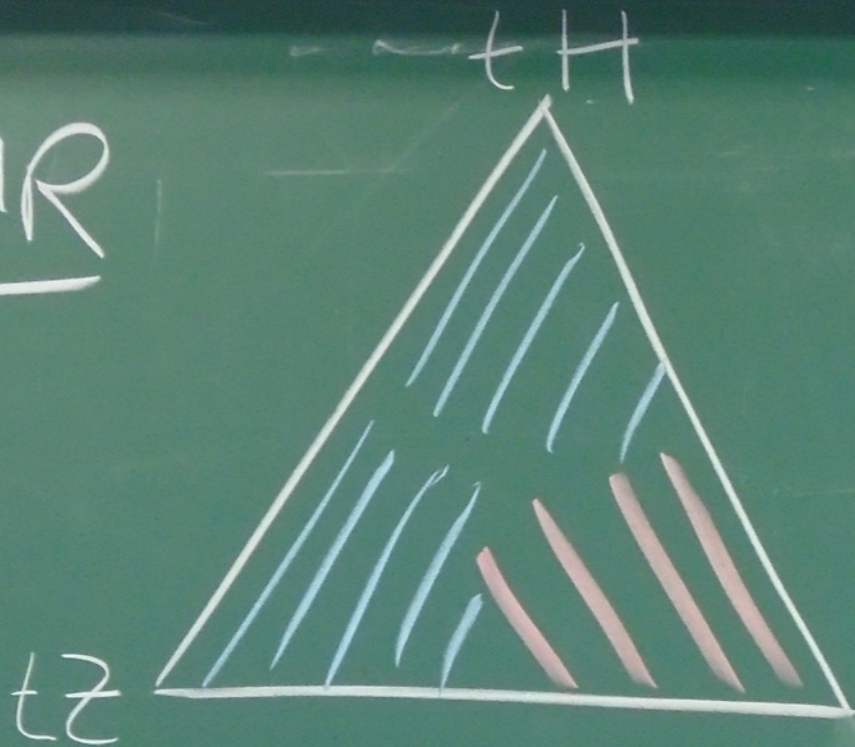


- Sensitivity for $m > 1$ TeV
- Similarly sensitive as leptonic analysis
- Interpretation:
 - singlet-BR: c_L^{bW} (much better limits)
 - doublet-BR: c_R^{tZ}

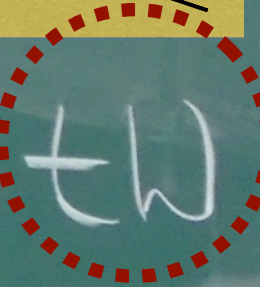
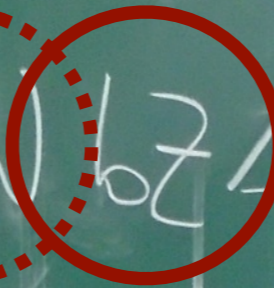
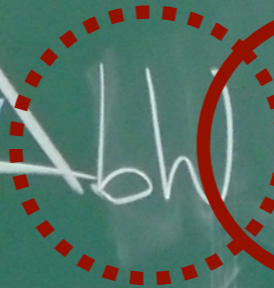
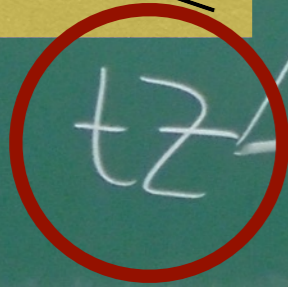
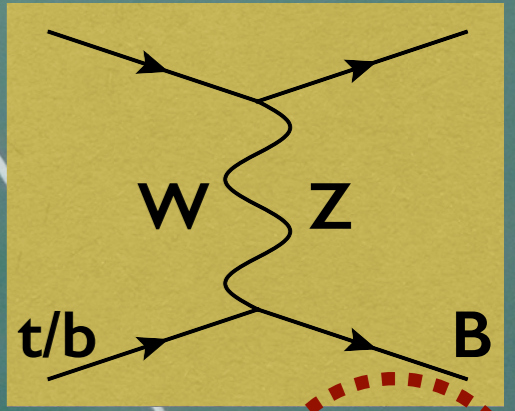
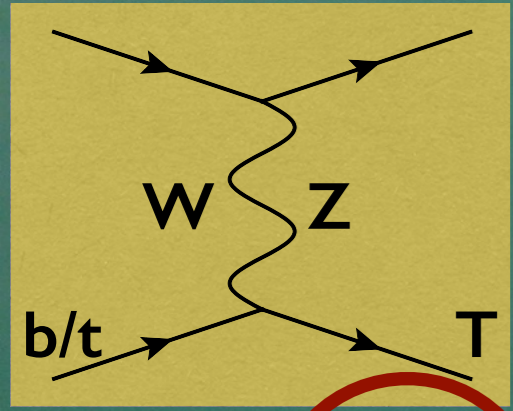
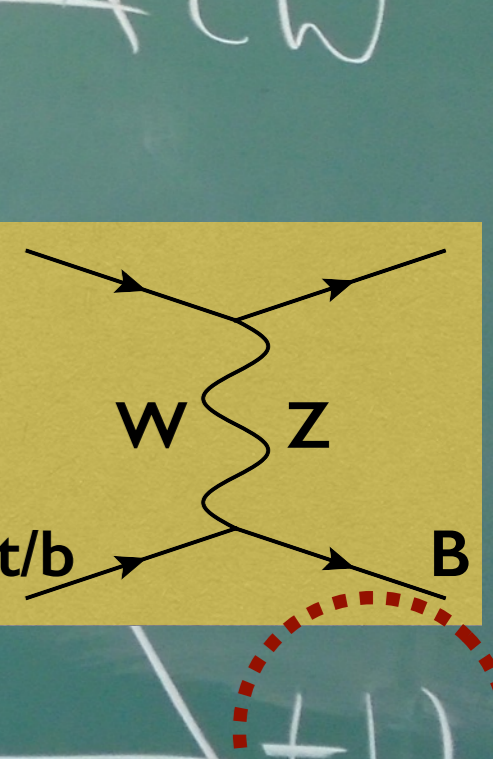
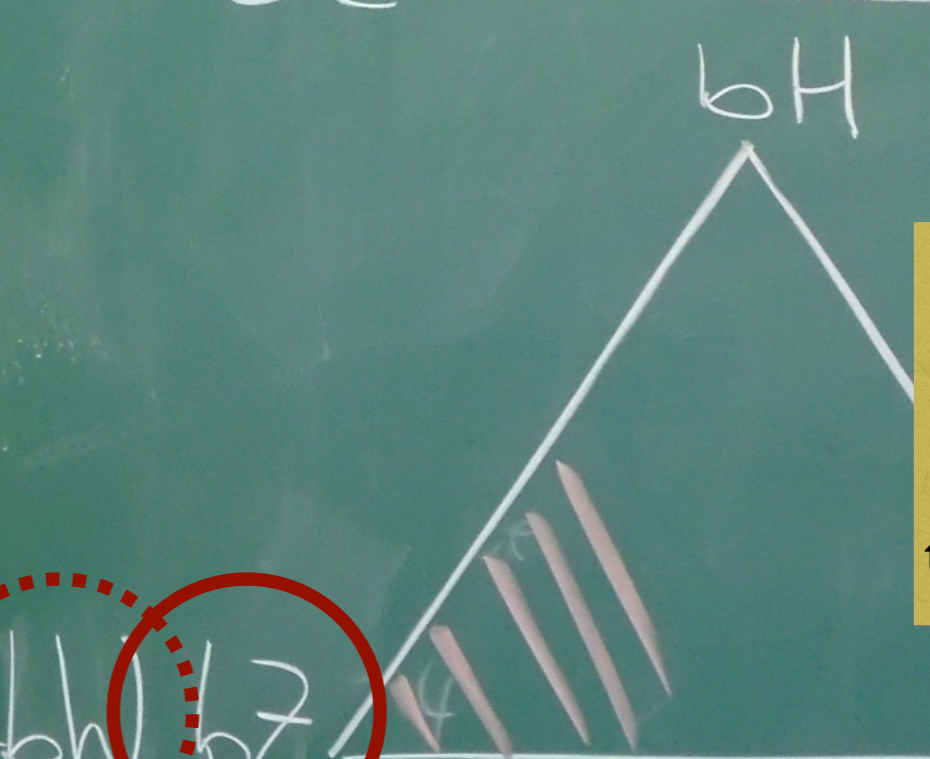
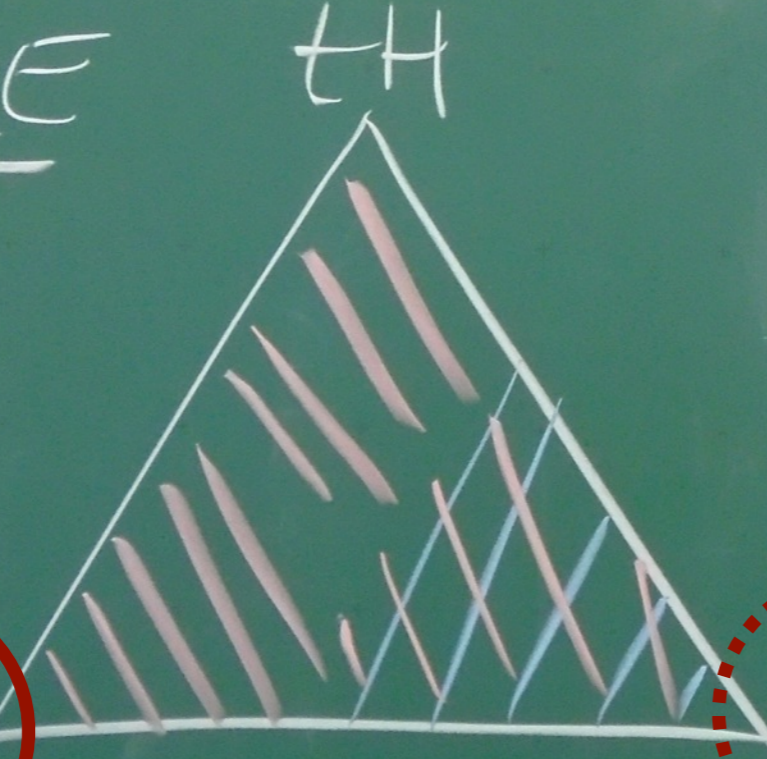
Single VLQ \rightarrow Zt / Zb



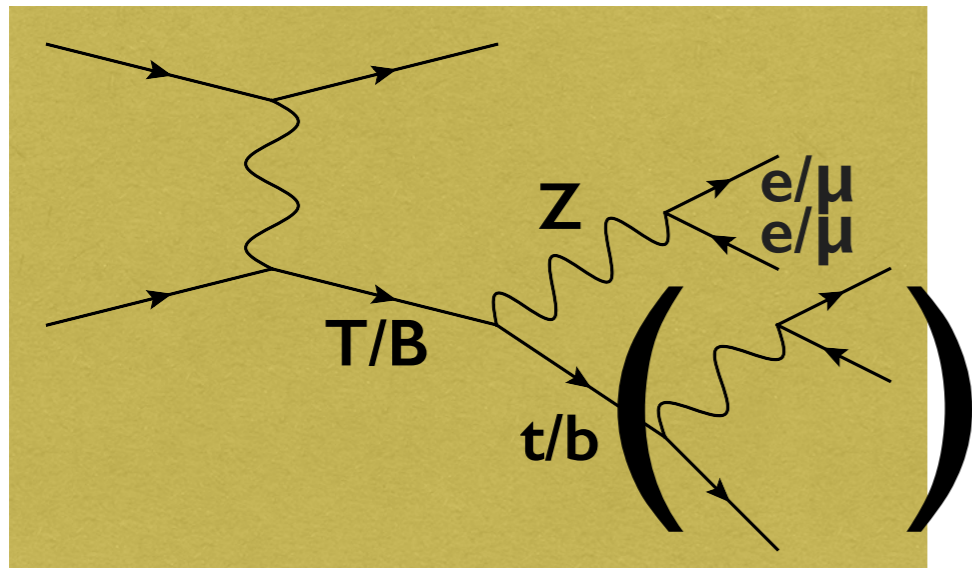
PAIR



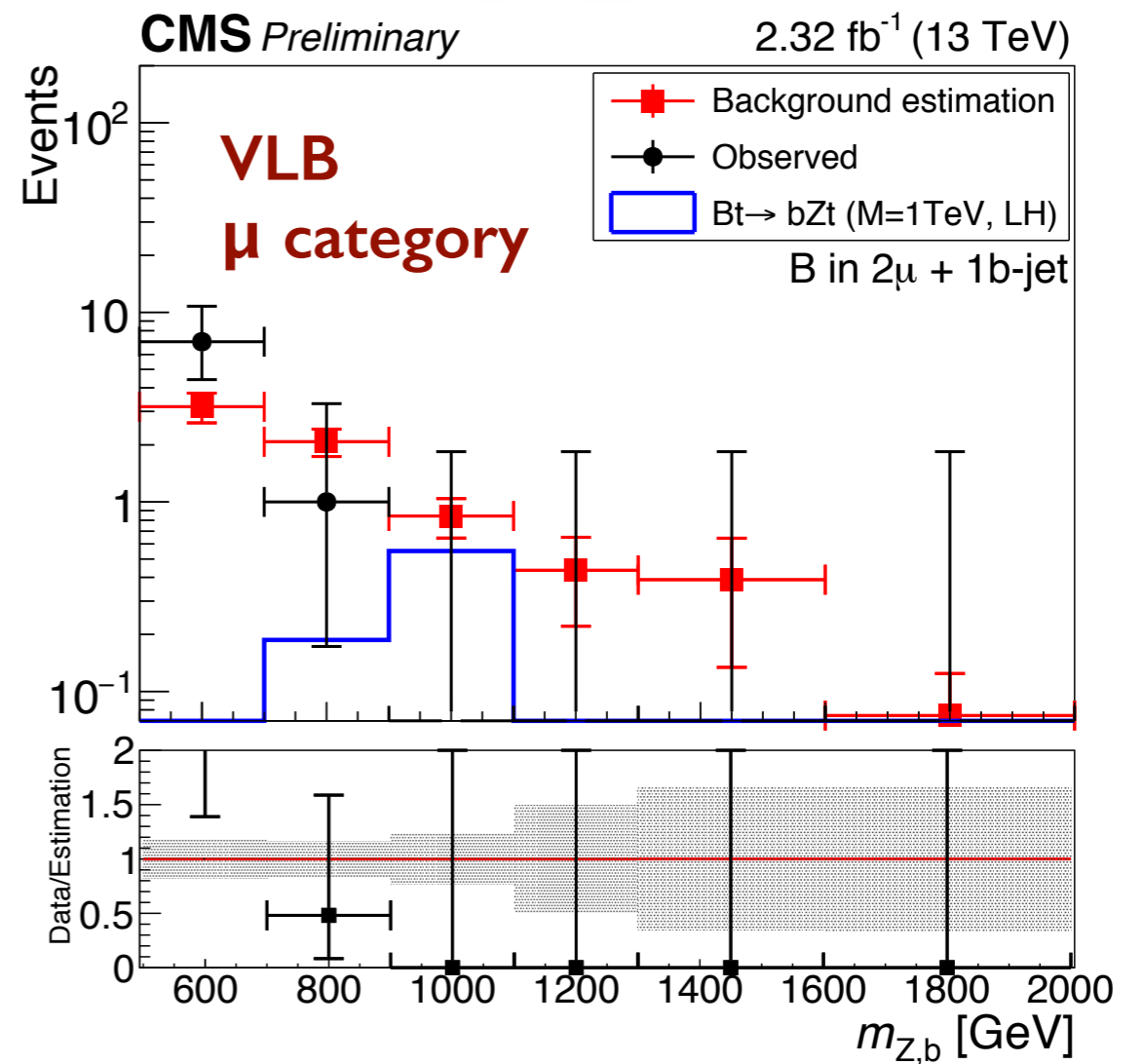
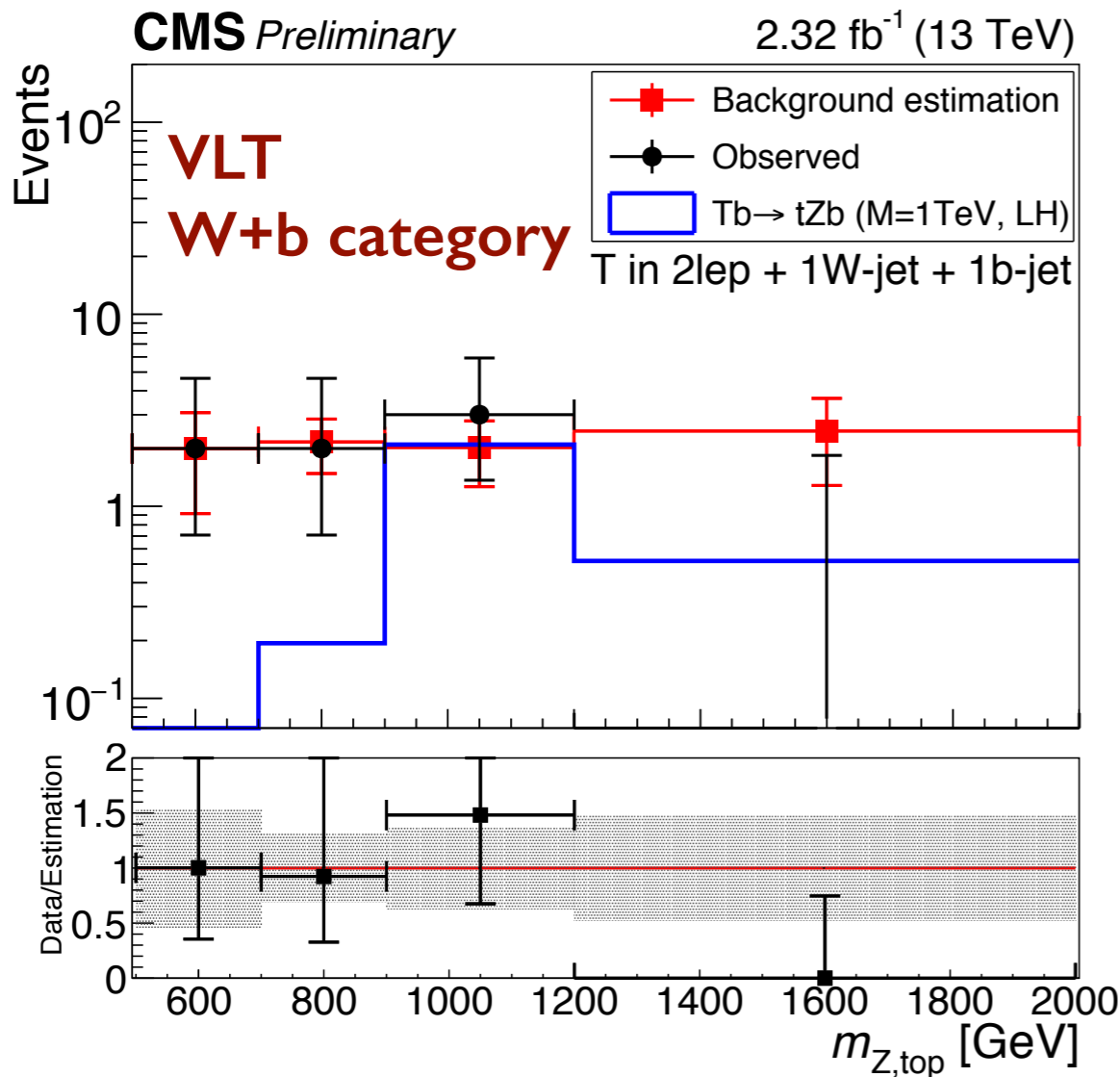
SINGLE

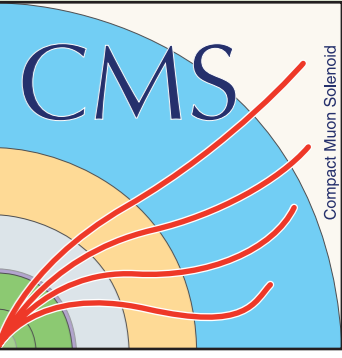


Single VLQ $\rightarrow Zt / Zb$



- Z from ee or $\mu\mu$ with small ΔR
- top: top-tag || W-tag+b || b+2j
- high leading lepton p_T
- VLT = Z + t
- VLB = Z + leading b

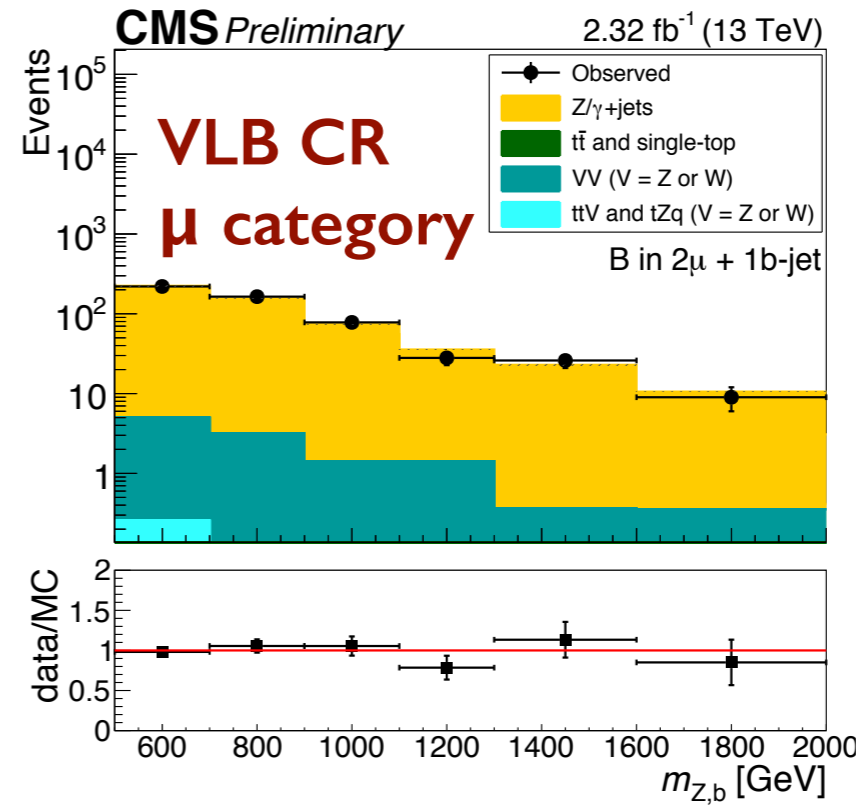
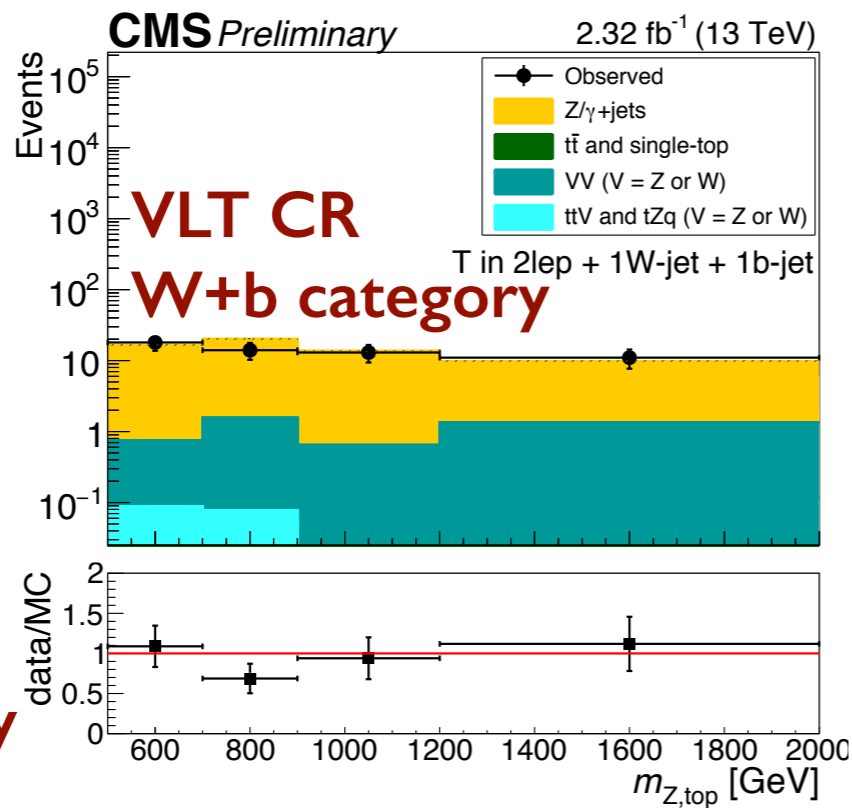




Single VLQ \rightarrow Zt / Zb

Background with 'α-method'

- scale all backgrounds to data in CR (0 b-tags)
- scale factors all close to 1 \rightarrow good !

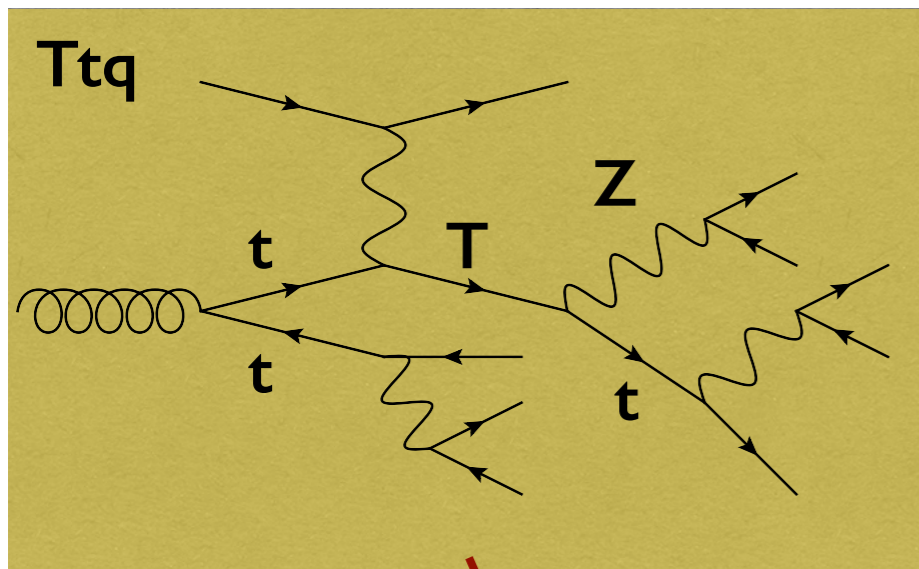


stat. uncertainty

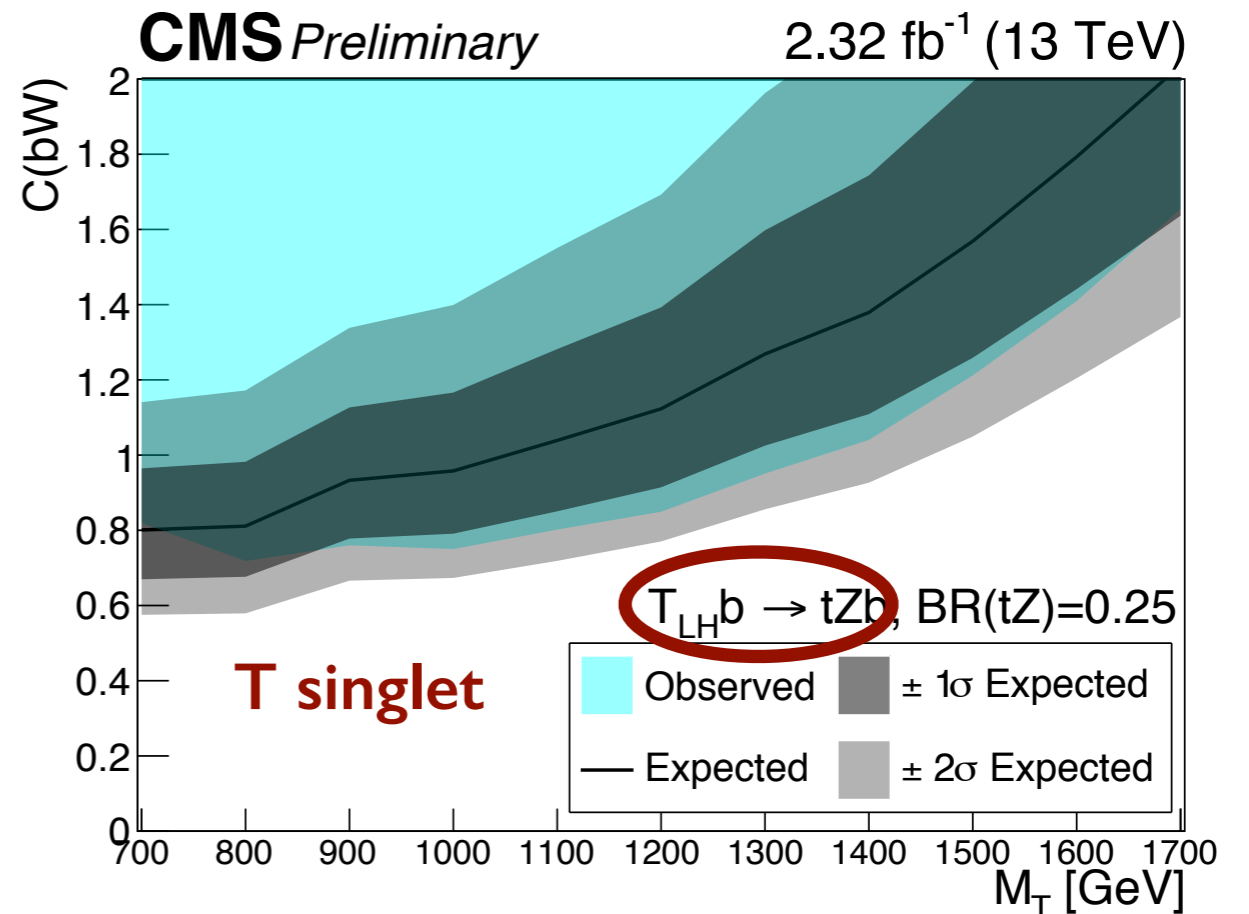
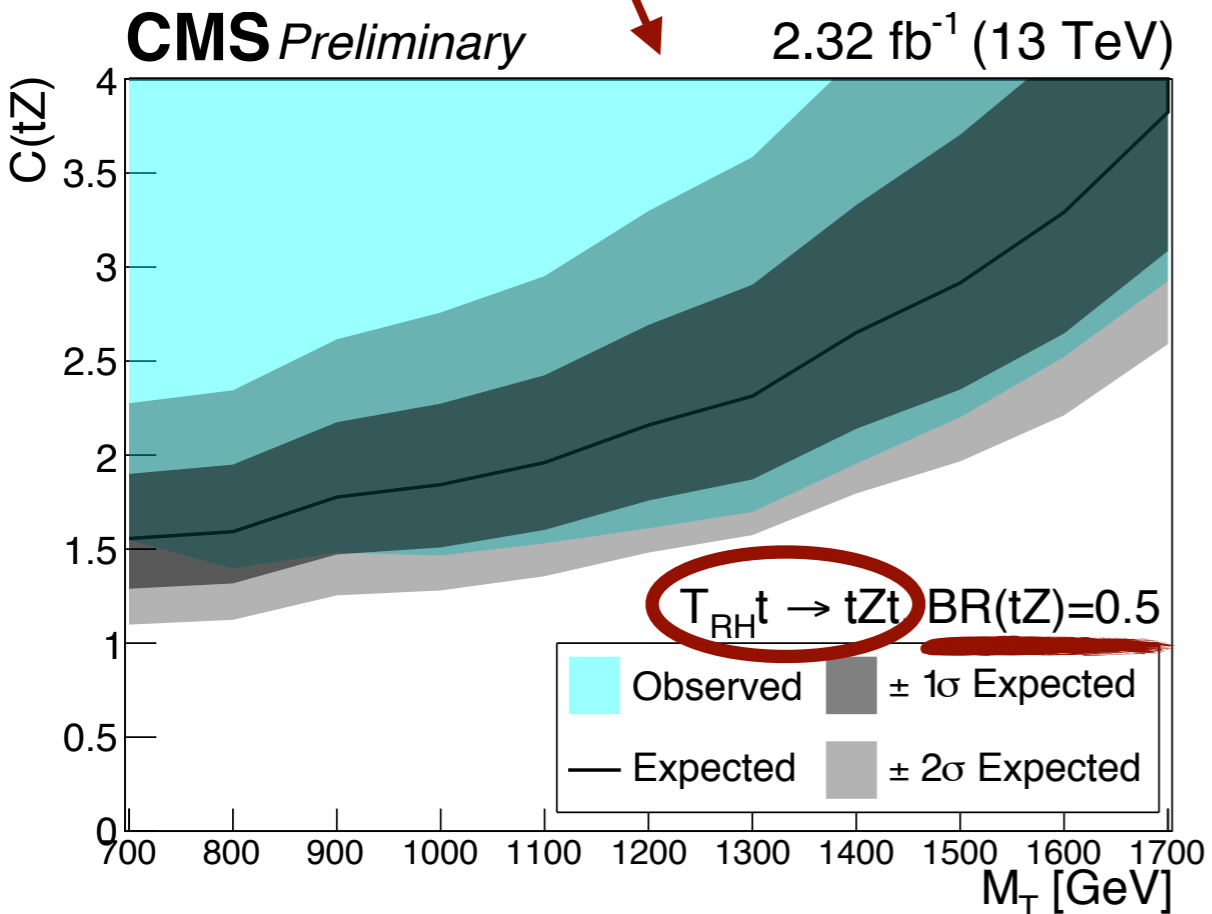
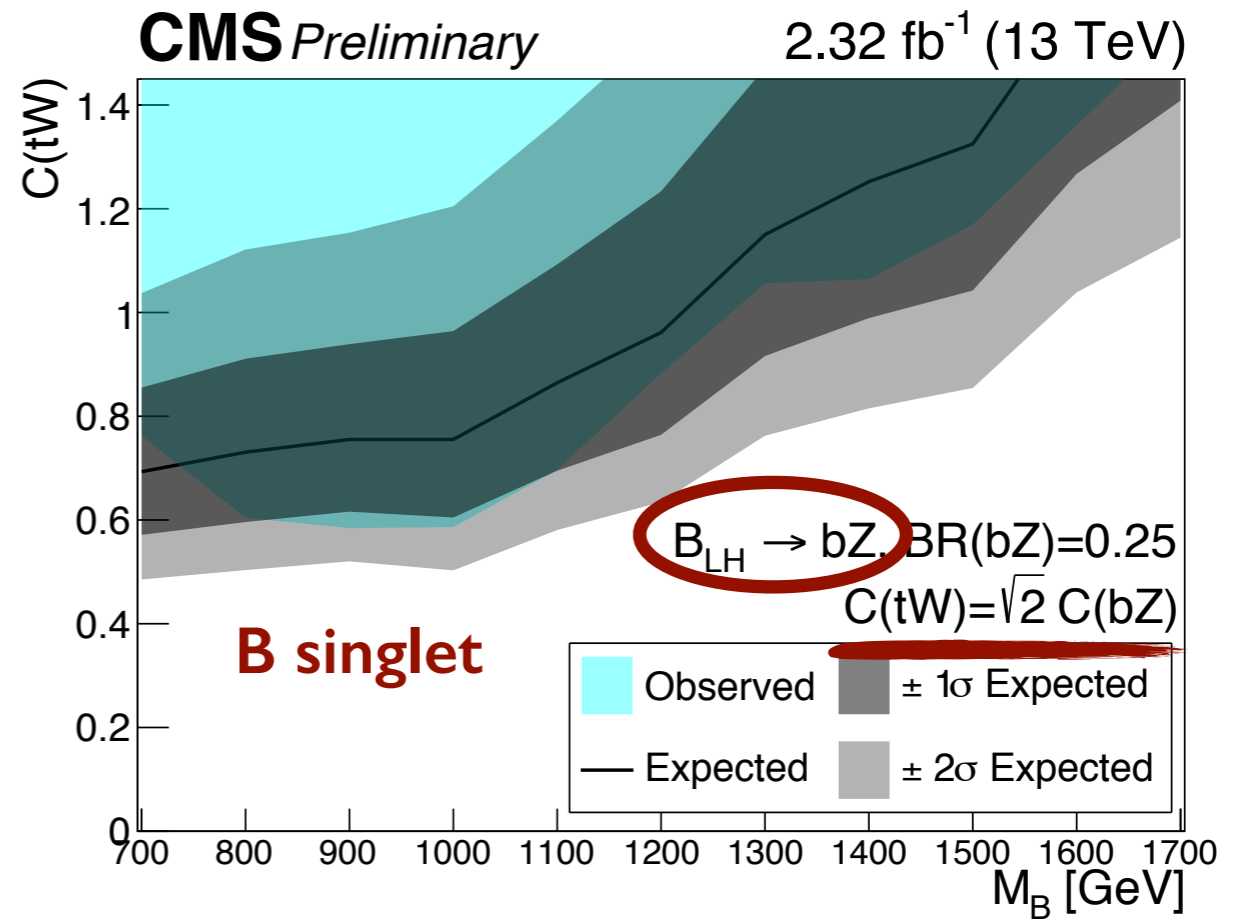
Channel	2l+1top-jet	2l+1W-jet+1b-jet	2μ+1b-jet+2jets	2e+1b-jet+2jets	2μ+1b-jet	2e+1b-jet
Background systematics on shape (range between bins)						
Background α-method	58%	29-32%	10-23%	13-32%	13-42%	17-40%
Closure test	8%	3-32%	3-60%	3-60%	3-60%	3-60%
b-tag	5%	2-6%	4-5%	4-6%	9-12%	6-16%
Z+jets composition	-	9-44%	3-22%	4-21%	2-13%	4-11%

closure test in data CR (!) w/ 2 jets

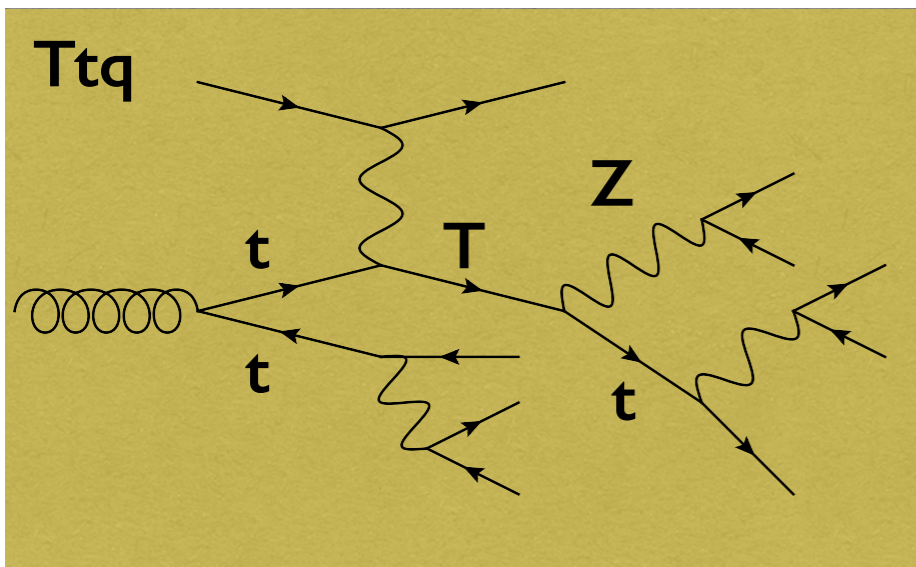
Single VLQ \rightarrow Zt / Zb



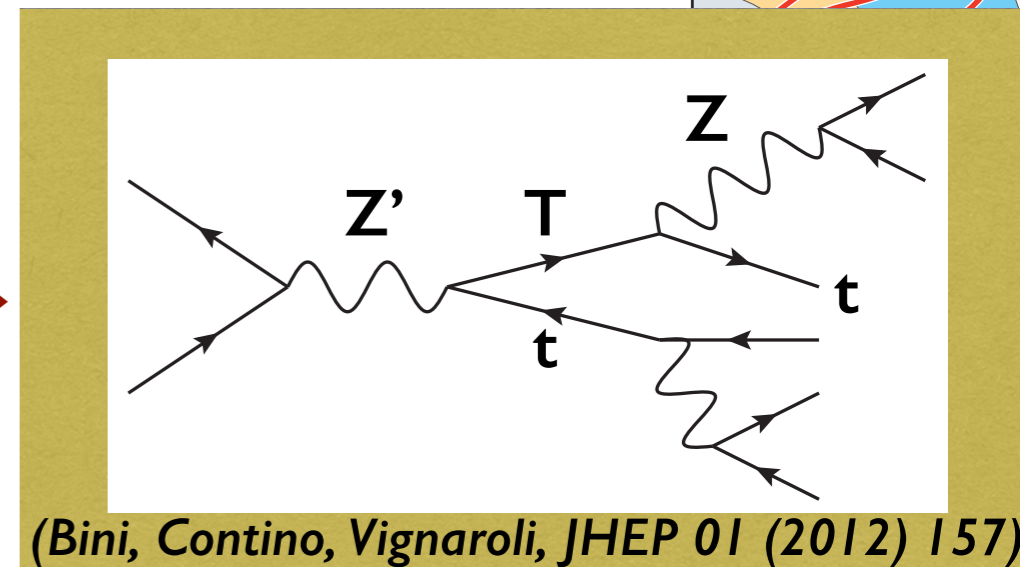
for (T,B) doublet
 $C^{bW} = 0$



CMS PAS B2G-16-001 (07/16) Reinterpretation : $Z' \rightarrow Tt \rightarrow Ztt$

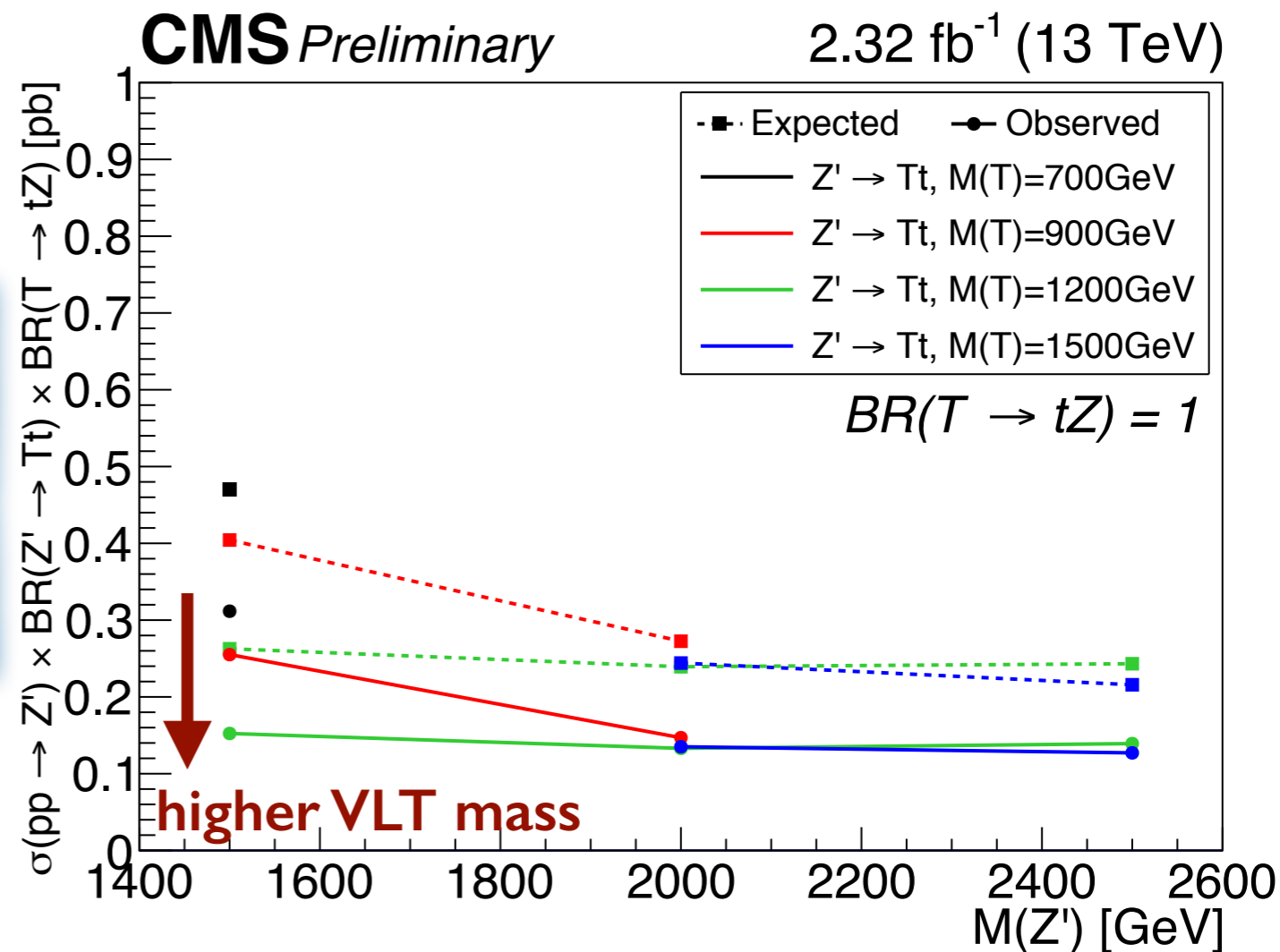


reinterpret



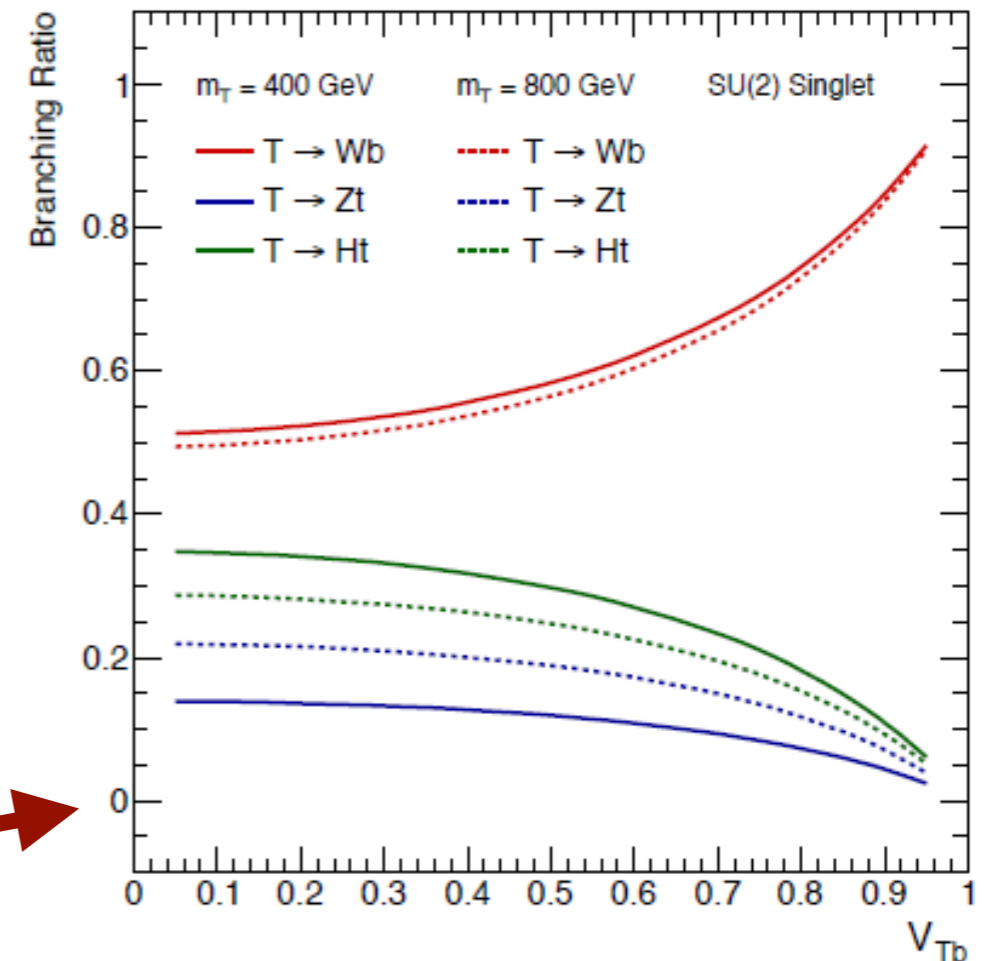
(Bini, Contino, Vignaroli, JHEP 01 (2012) 157)

- assume $BR(T \rightarrow tZ) = 100\%$
- limits improve when more boosted
 - with higher $m(T)$
 - with higher $m(Z')$



Challenges for Interpretation

- Experimental assumptions
 - VLQ width effects on exp. observables ?
 - LH/RH differences in exp. observables ?
 - basis for 'BR reweighting'
 - pair and single production ?
 - additional production mechanisms ?
(for ex. via heavy $G \rightarrow \text{VLQ} + q$
or heavy $G \rightarrow 2 \text{VLQ}$)
- Interpretation
 - BRs : small coupling approximation ?
 - additional production mechanisms ?
 - Coupling to 1st/2nd generation ?
 - More than one VLQ multiplet ?
 - Extended scalar sector ?
 - allow recasting via HEPData info ?
 - publish σ limits for full BR triangle ?

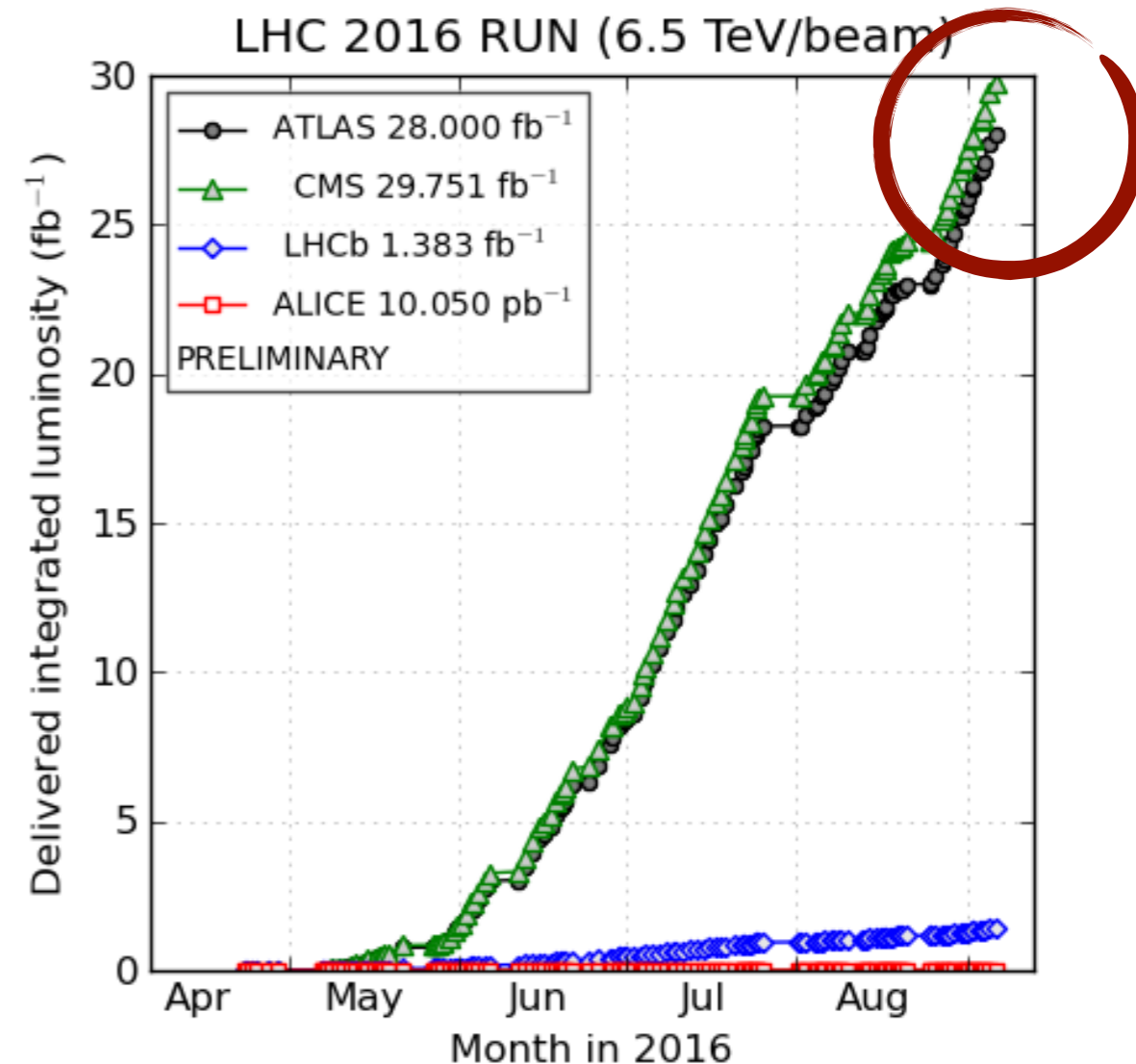


BR vs. V_{Tb}
SU(2) singlet T @ $m_T = 400, 800$ GeV

Conclusions

- Broad search program for VLQ
- Focus shifted towards single production
 - But pair production not forgotten !
 - Limits approaching 1 TeV
- Experimental methods
 - Variety of background methods reassuring
 - Time for boosted strategies has come
- Interpretation
 - More tricky with growing interest in single production

VLQ @ 1.X TeV ?



(2016-09-06 11:37 including fill 5279; scripts by C. Barschel)

Backup

Impact of couplings on kinematics

Aguilar-Saavedra, JHEP 11 (2009) 030

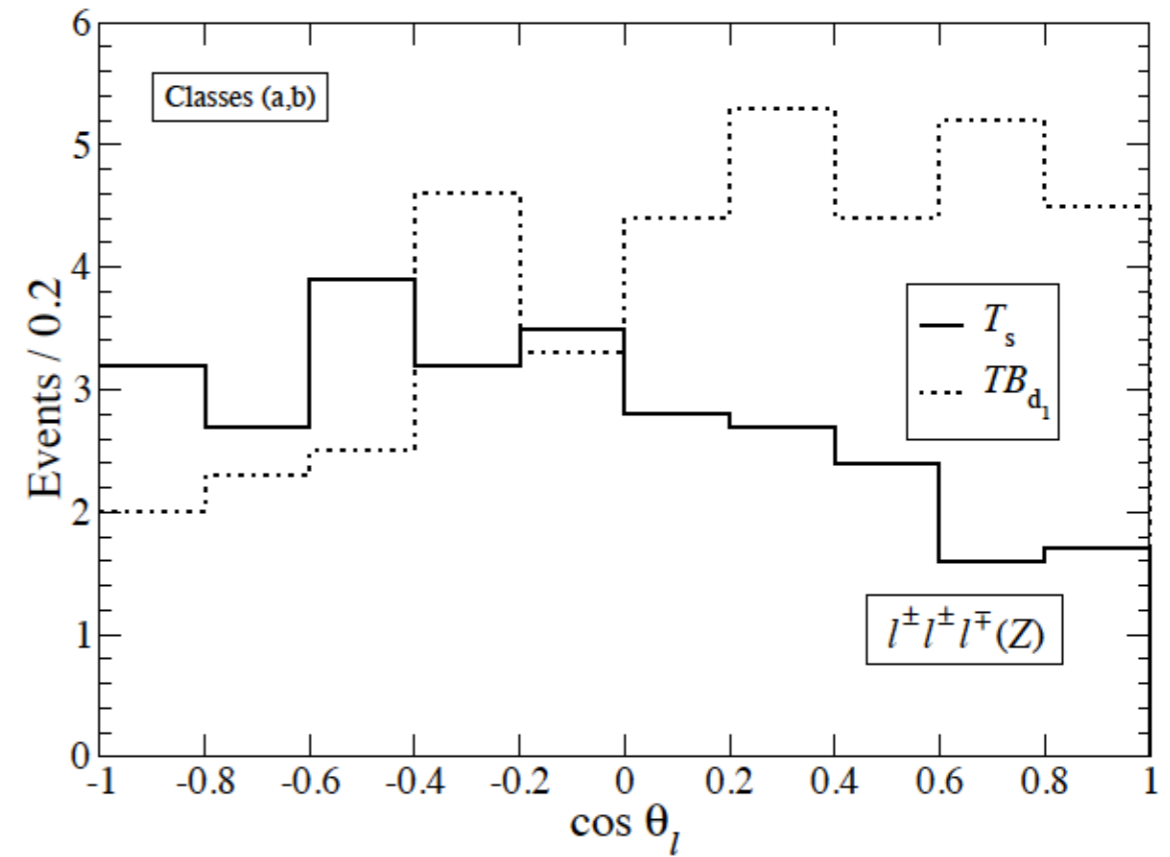
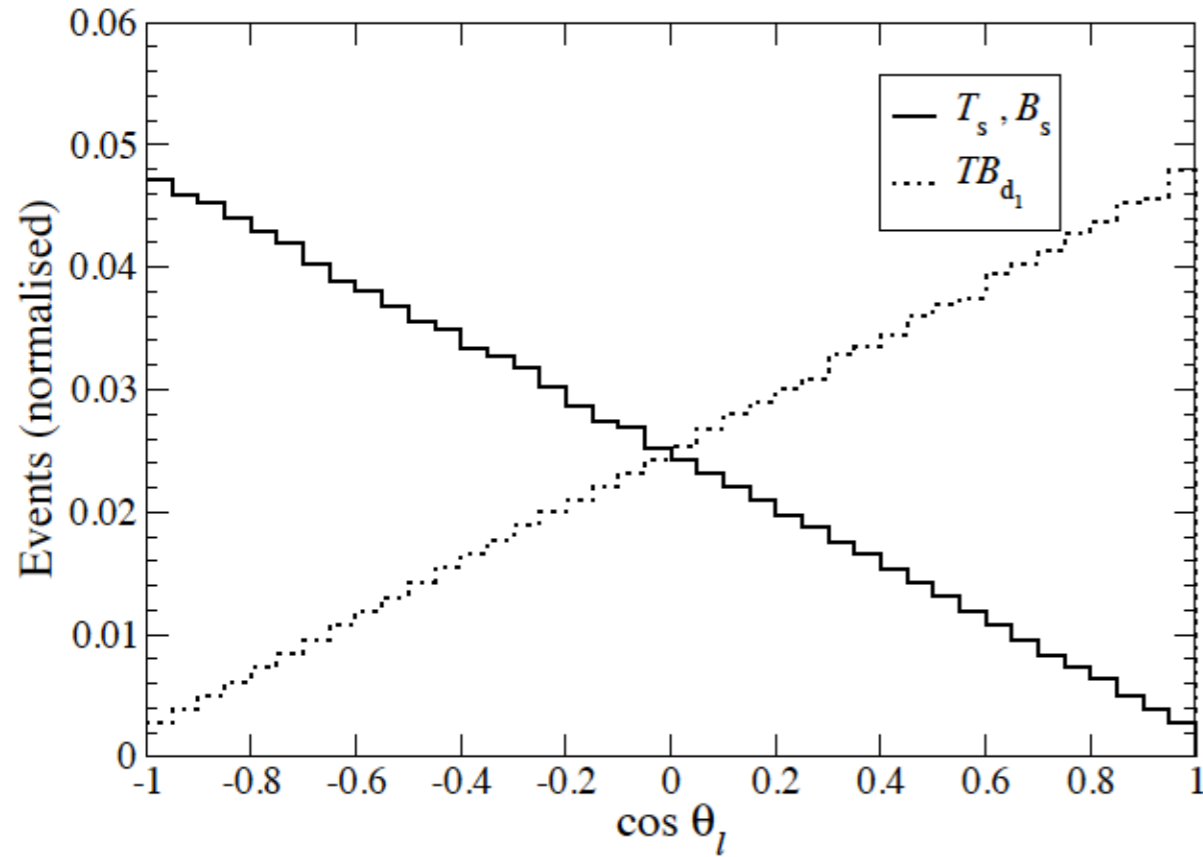
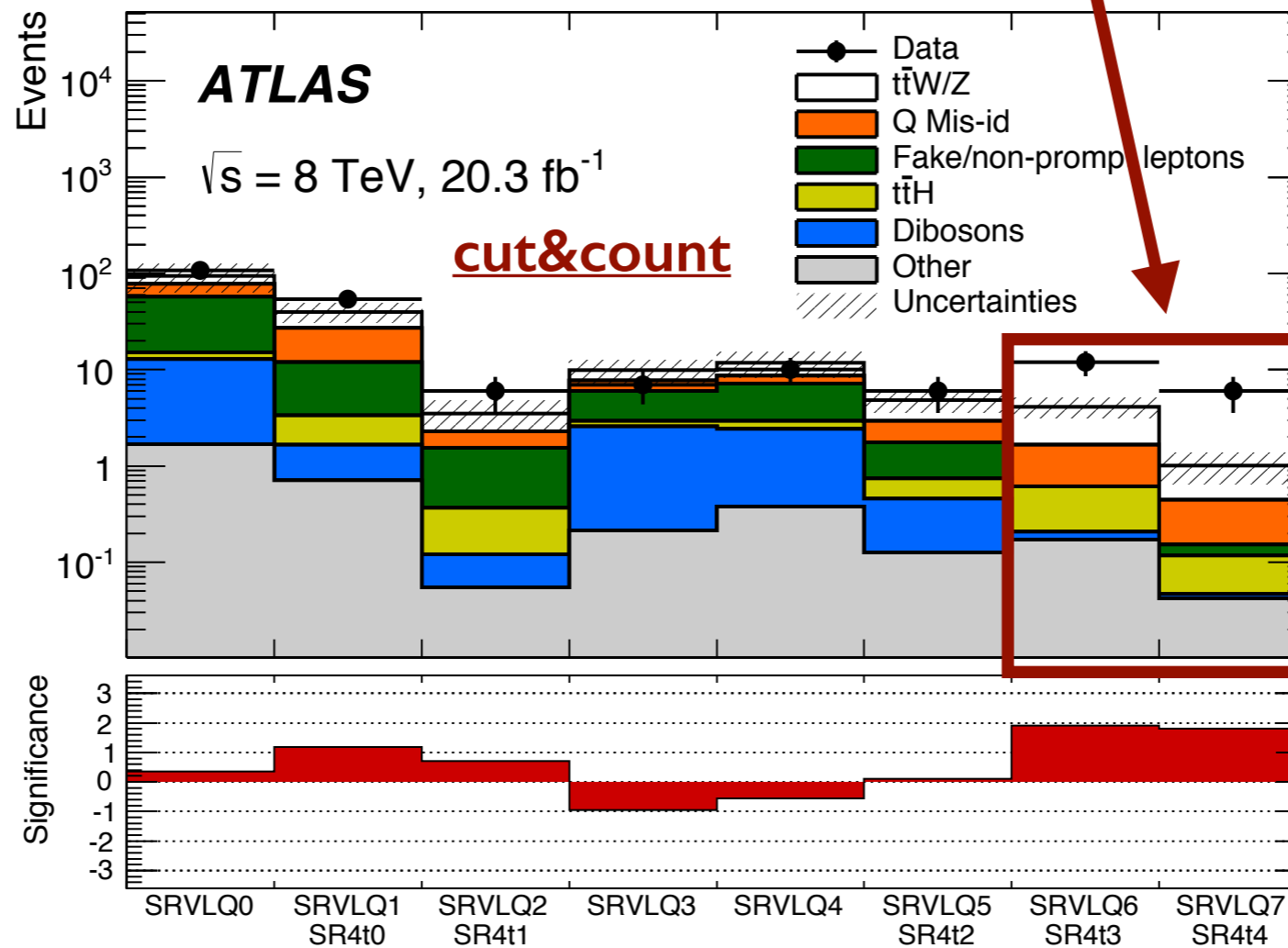


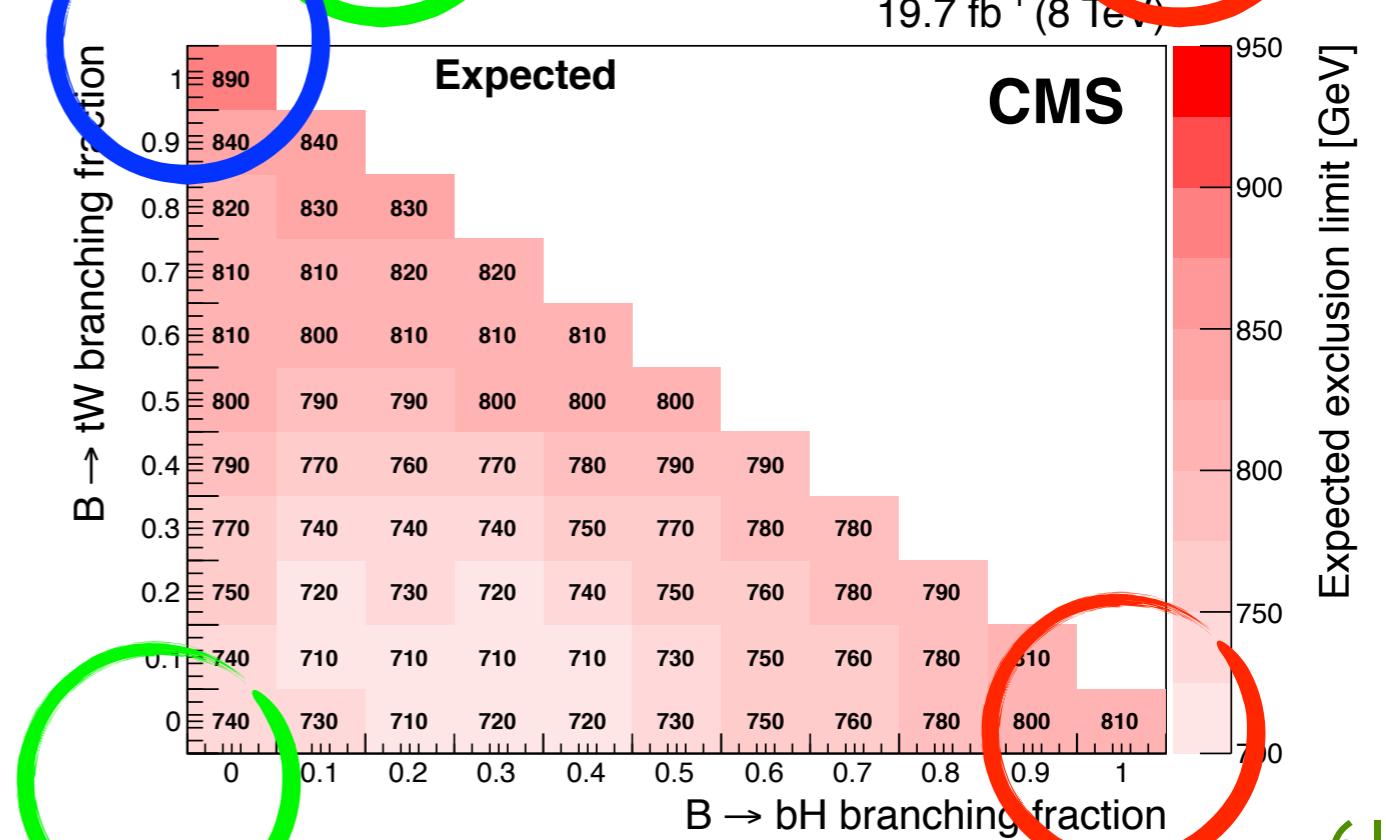
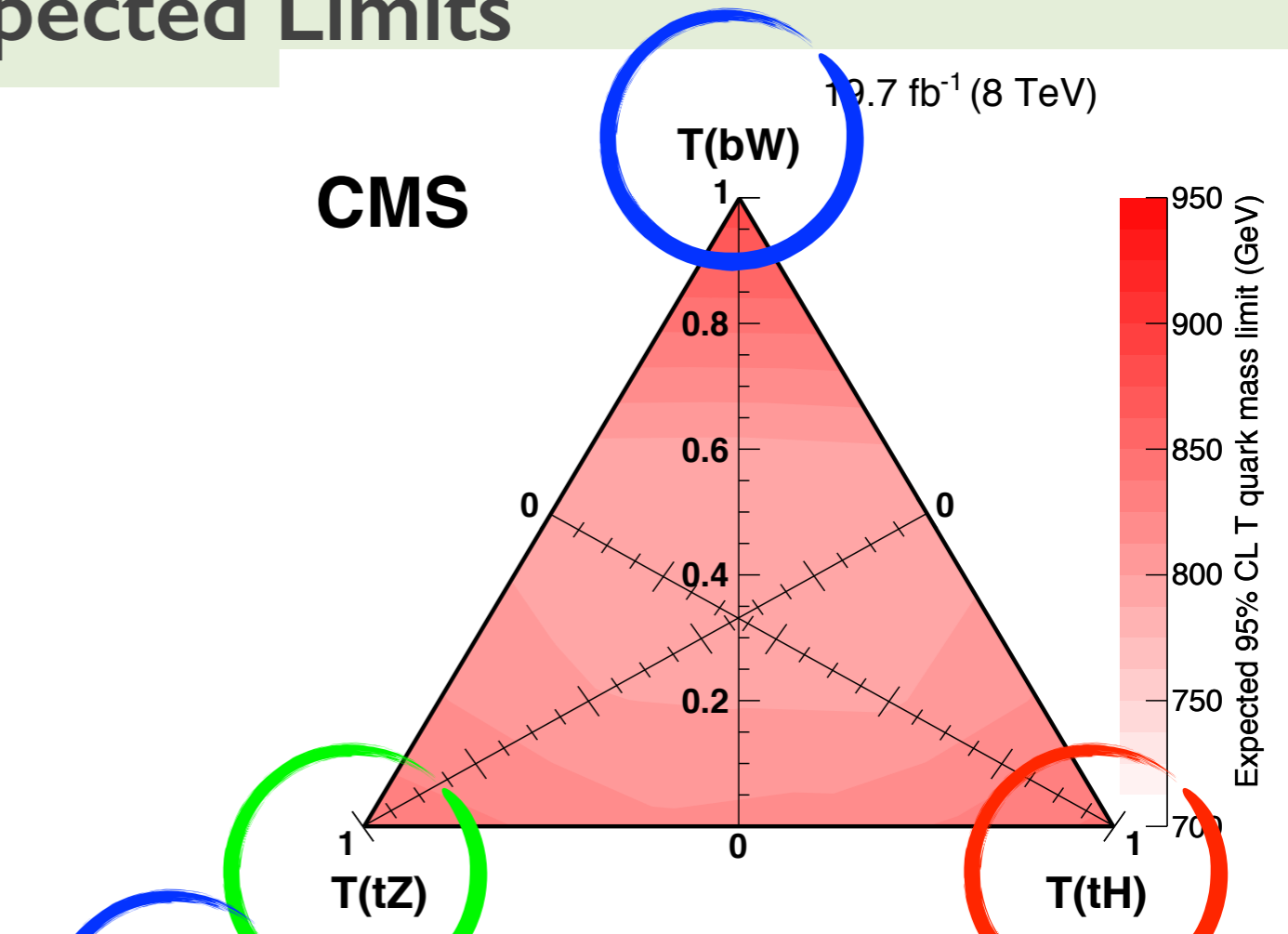
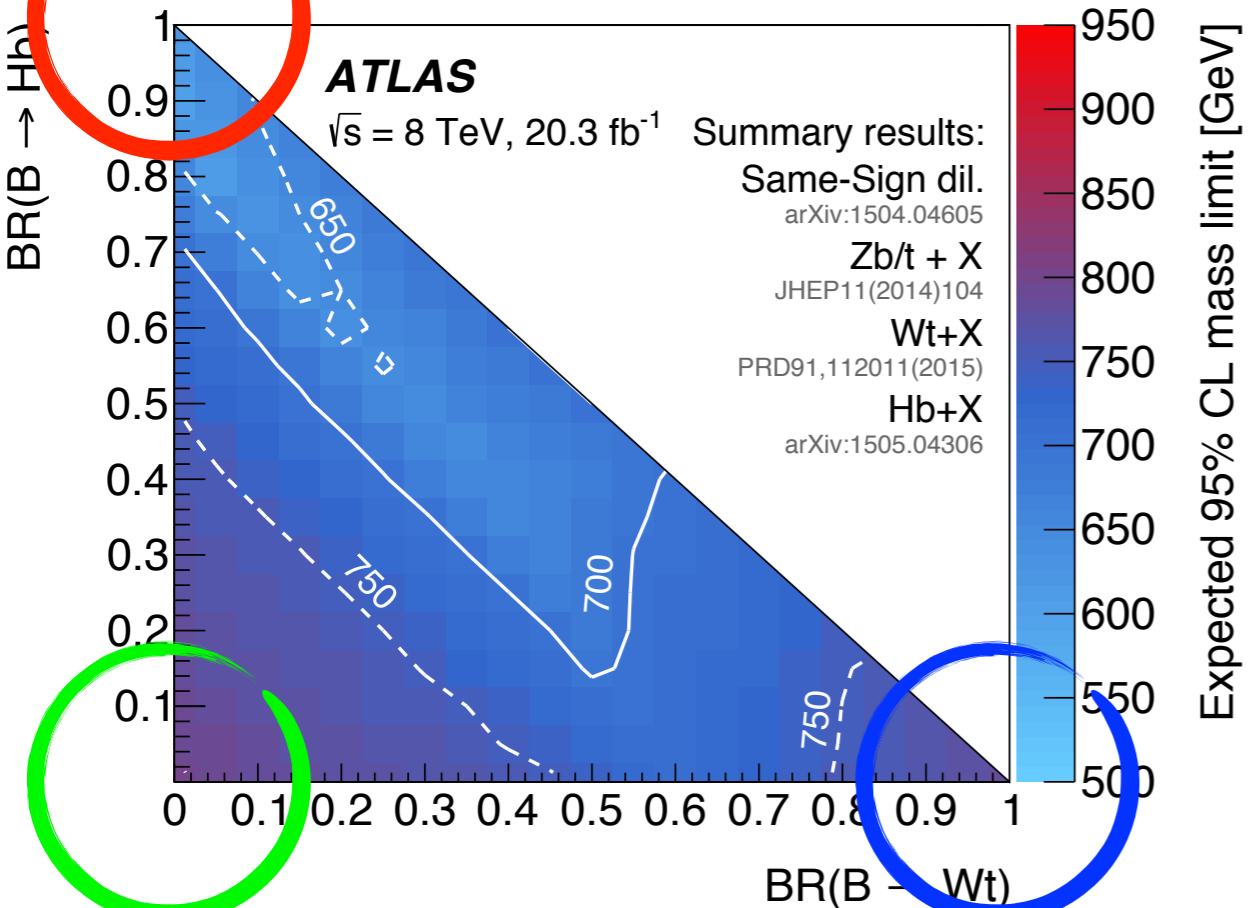
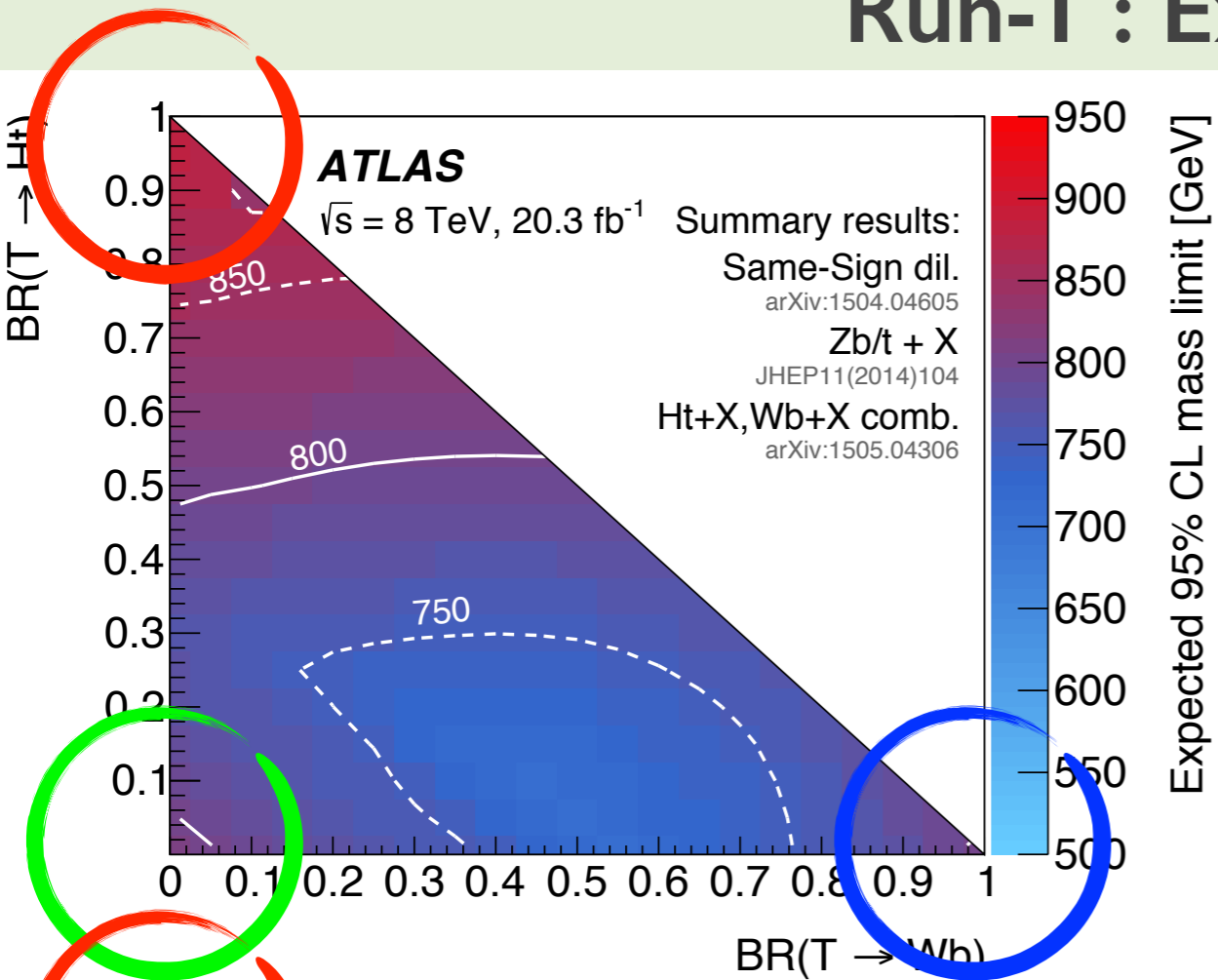
Figure 9: Left: Charged lepton distribution in the top quark rest frame for $T \rightarrow Zt$ and $B \rightarrow W^-t$ decays. Right: distribution for the T singlet and (TB) doublet after simulation.

Same-sign leptons + b-quarks

Definition		Name
$e^\pm e^\pm + e^\pm \mu^\pm + \mu^\pm \mu^\pm + eee + ee\mu + e\mu\mu + \mu\mu\mu, N_j \geq 2$		
$400 < H_T < 700 \text{ GeV}$	$N_b = 1$	SRVLQ0
	$N_b = 2$	SRVLQ1
	$N_b \geq 3$	SRVLQ2
	$N_b = 1$	SRVLQ3
		SRVLQ4
$H_T \geq 700 \text{ GeV}$	$N_b = 2$	SRVLQ5
		SRVLQ6
	$N_b \geq 3$	SRVLQ7
$e^+e^+, e^+\mu^+, \mu^+\mu^+, N_j \in [2, 4], \Delta\phi_{\ell\ell} > 2.5$		
$H_T > 450 \text{ GeV}$	$N_b \geq 1$	SRttee, SRttem, SRttμμ



Run-I : Expected Limits

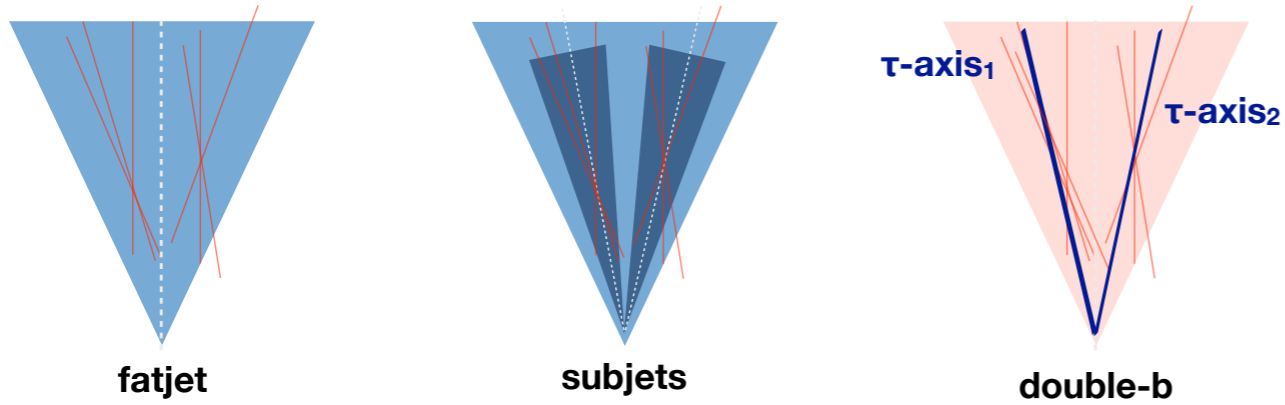


ATLAS-CONF-2016-032

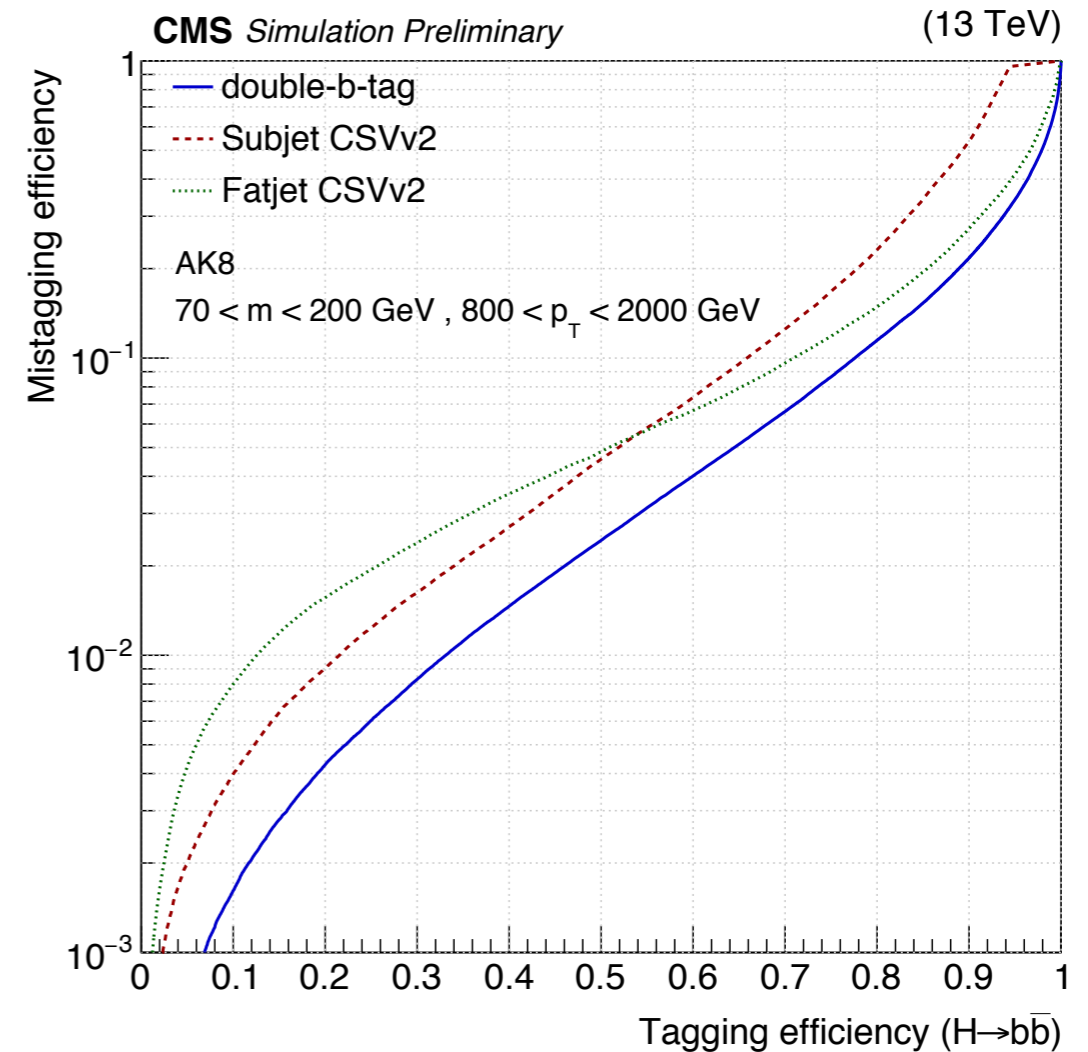
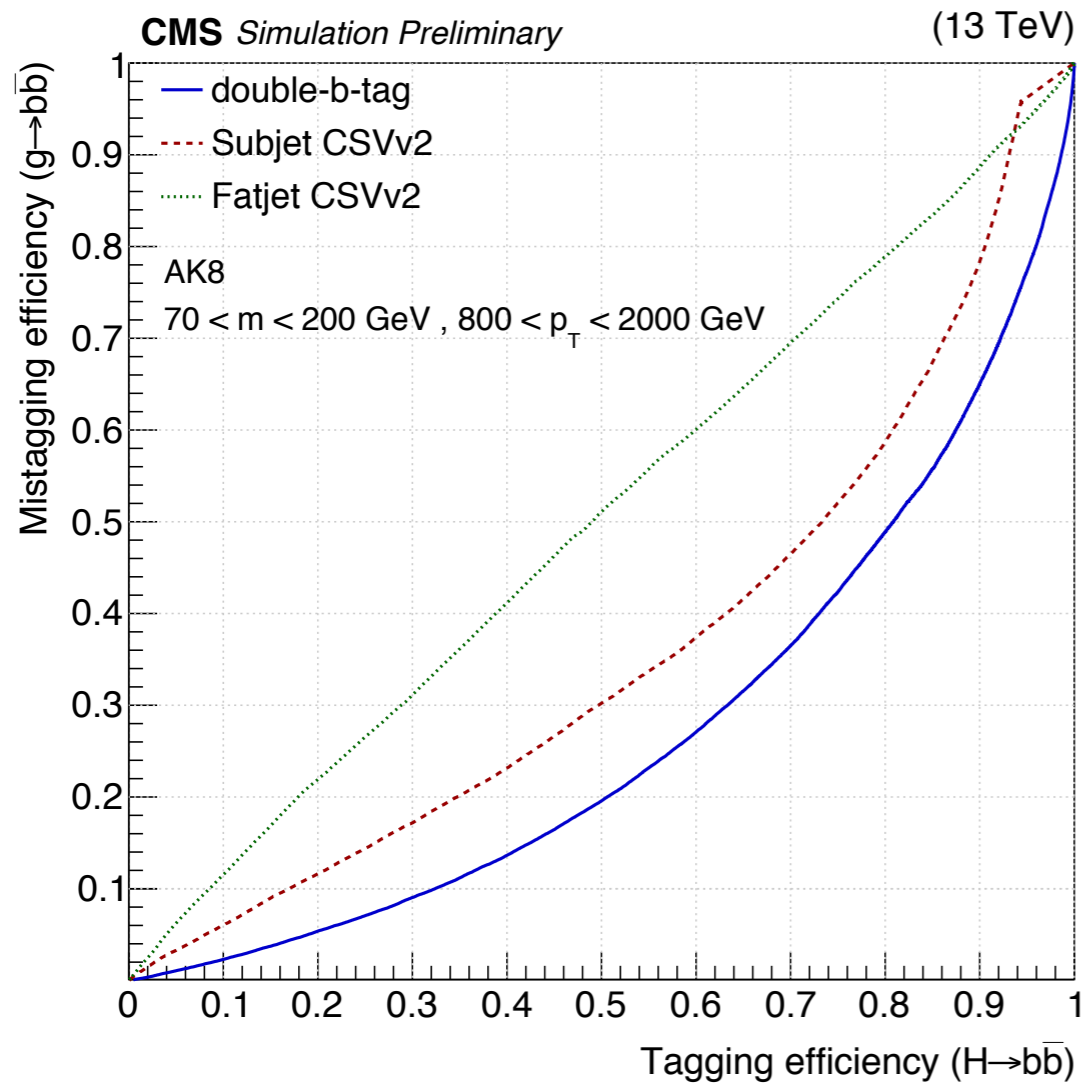
	SR0	SR1	SR2	SR3	SR4
Fake/Non-prompt	16.3± 9.5	4.2 ±3.3	1.0 ± 0.9	1.8 ± 1.4	7.1±4.5
Charge mis-ID	18.1± 4.1	14.9±3.5	1.2 ± 0.3	1.5 ± 0.4	2.1±0.5
$t\bar{t}W/Z/W^+W^-$	10.1± 1.4	9.2 ±1.3	1.0 ± 0.3	2.2 ± 0.3	3.1±0.5
Dibosons	5.8 ± 1.0	0.5 ±0.2	0.03±0.07	1.6 ± 0.4	1.8±0.4
Other bkg.	2.0 ± 1.0	1.7 ±0.9	0.3 ± 0.2	0.3 ± 0.2	0.5±0.3
Total bkg.	52 ± 11	31 ± 5	3.6 ± 1.0	7.4 ± 1.5	15 ± 5
$t\bar{t}t\bar{t}$ (SM)	0.5 ± 0.1	0.8 ±0.1	0.9 ± 0.1	0.2 ± 0.1	0.5±0.1
$t\bar{t}t\bar{t}$ (CI)	0.26±0.04	0.6 ±0.1	0.6 ± 0.1	0.24±0.05	0.9±0.1
UED 1.2 TeV	<0.01	<0.01	<0.01	0.3 ± 0.1	3.8±0.8
$T\bar{T}$ 0.75 TeV	0.2 ± 0.1	0.31±0.1	0.04±0.04	0.9 ± 0.2	3.7±0.4
Data	51	37	3	4	11
mis-ID fraction	35%	48%	33%	20%	14%
	SR5	SR6	SR7		
Fake/Non-prompt	1.4±0.9	2.6±1.8	0.0 ±0.6		
Charge mis-ID	1.4±0.4	1.6±0.5	0.6 ±0.2		
$t\bar{t}W/Z/W^+W^-$	2.3±0.6	3.0±0.7	0.8 ±0.4		
Dibosons	0.3±0.1	0.2±0.1	0.0 ±0.1		
Other bkg.	0.4±0.2	0.7±0.4	0.5 ±0.3		
Total bkg.	5.8±1.2	8.1±2.0	1.9 ±0.8		
$t\bar{t}t\bar{t}$ (SM)	0.7±0.1	1.8±0.2	3.6 ±0.4		
$t\bar{t}t\bar{t}$ (CI)	0.6±0.1	2.2±0.2	5.2 ±0.4		
UED 1.2 TeV	0.6±0.1	6.6±0.7	10.1±0.8		
$T\bar{T}$ 0.75 TeV	1.3±0.2	5.0±0.5	3.2 ±0.4		
Data	6	3	2		
	24%	20%	32%		

CMS 13.6% total mis-ID fraction

CMS PAS BTV-15-002

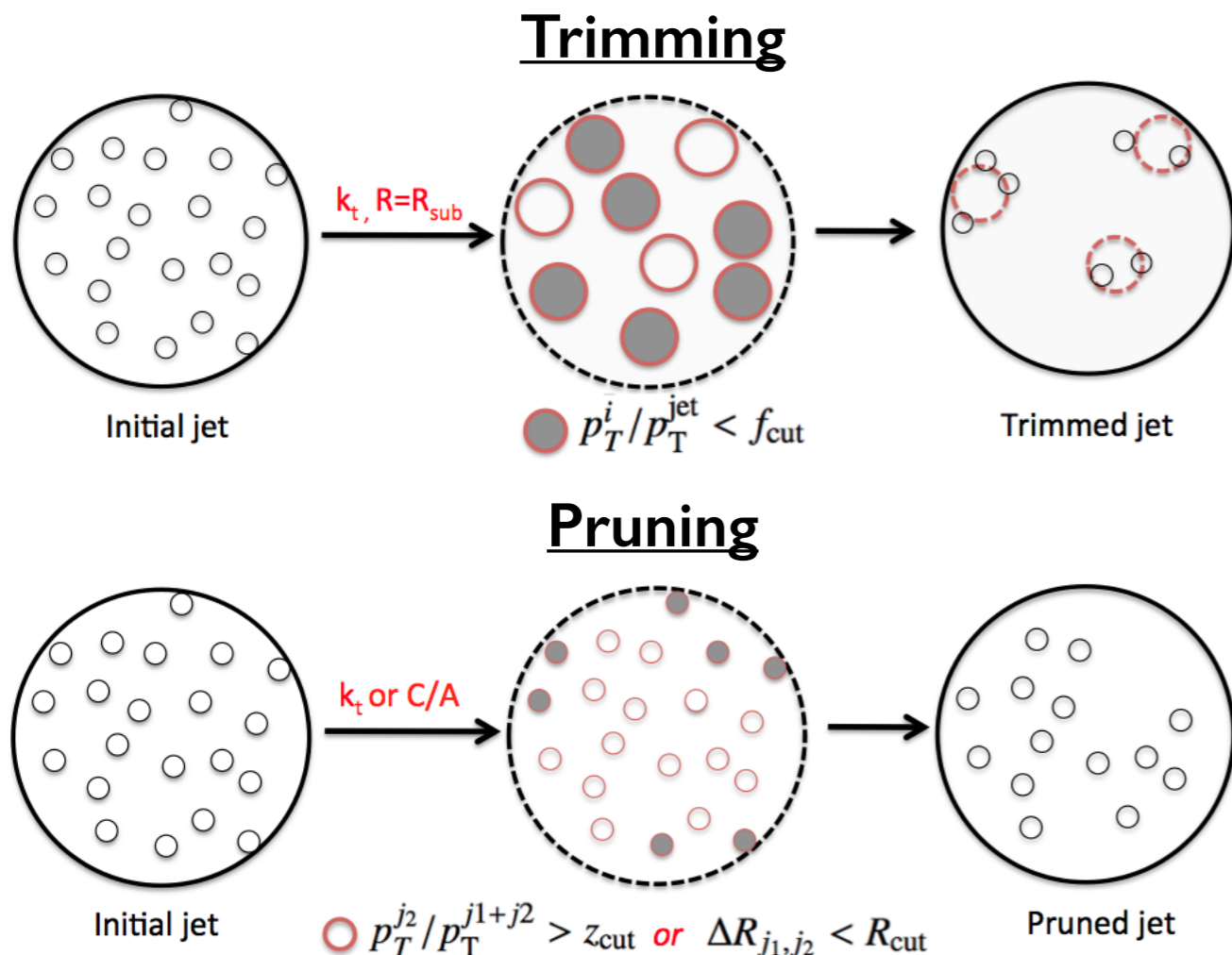


$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k}\}$$



Grooming Techniques

ATL-PHYS-PUB-2015-033

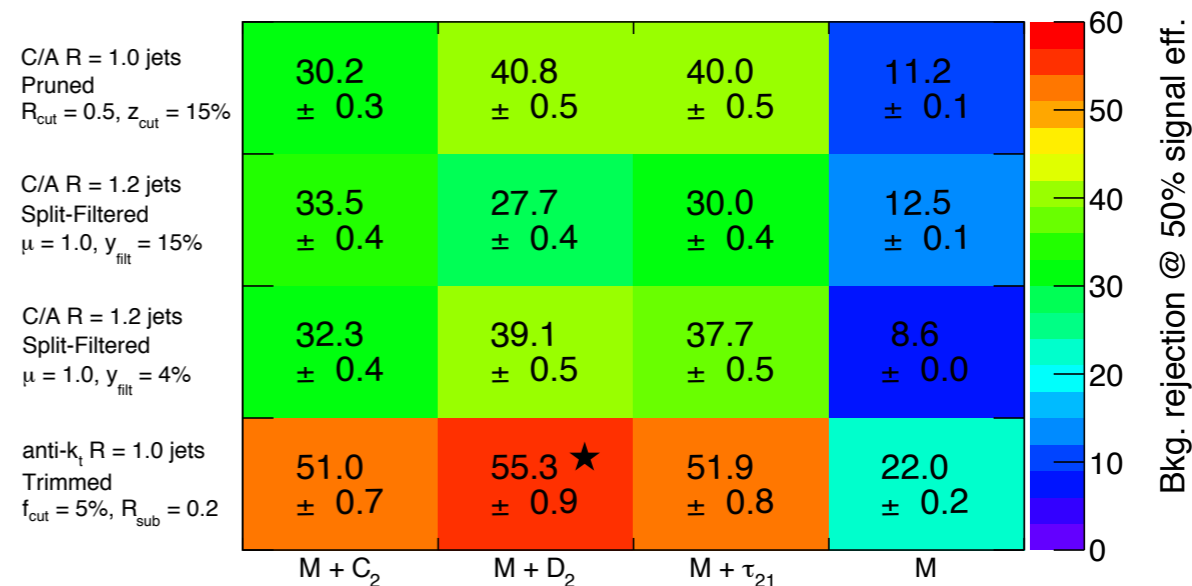


illustrations from JHEP 09 (2013) 076

Soft Drop Condition:
$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0} \right)^\beta$$

Larkoski, Marzani, Soyez, Thaler, JHEP 05 (2014) 146

ATLAS Simulation Preliminary
 $\sqrt{s} = 13 \text{ TeV}$ ★ = Optimal grooming + tagging combination
 $|\eta^{Truth}| < 2.0, 200 < p_T^{Truth} < 350 \text{ GeV}, M^{Reco} \text{ Cut}$ W-jets



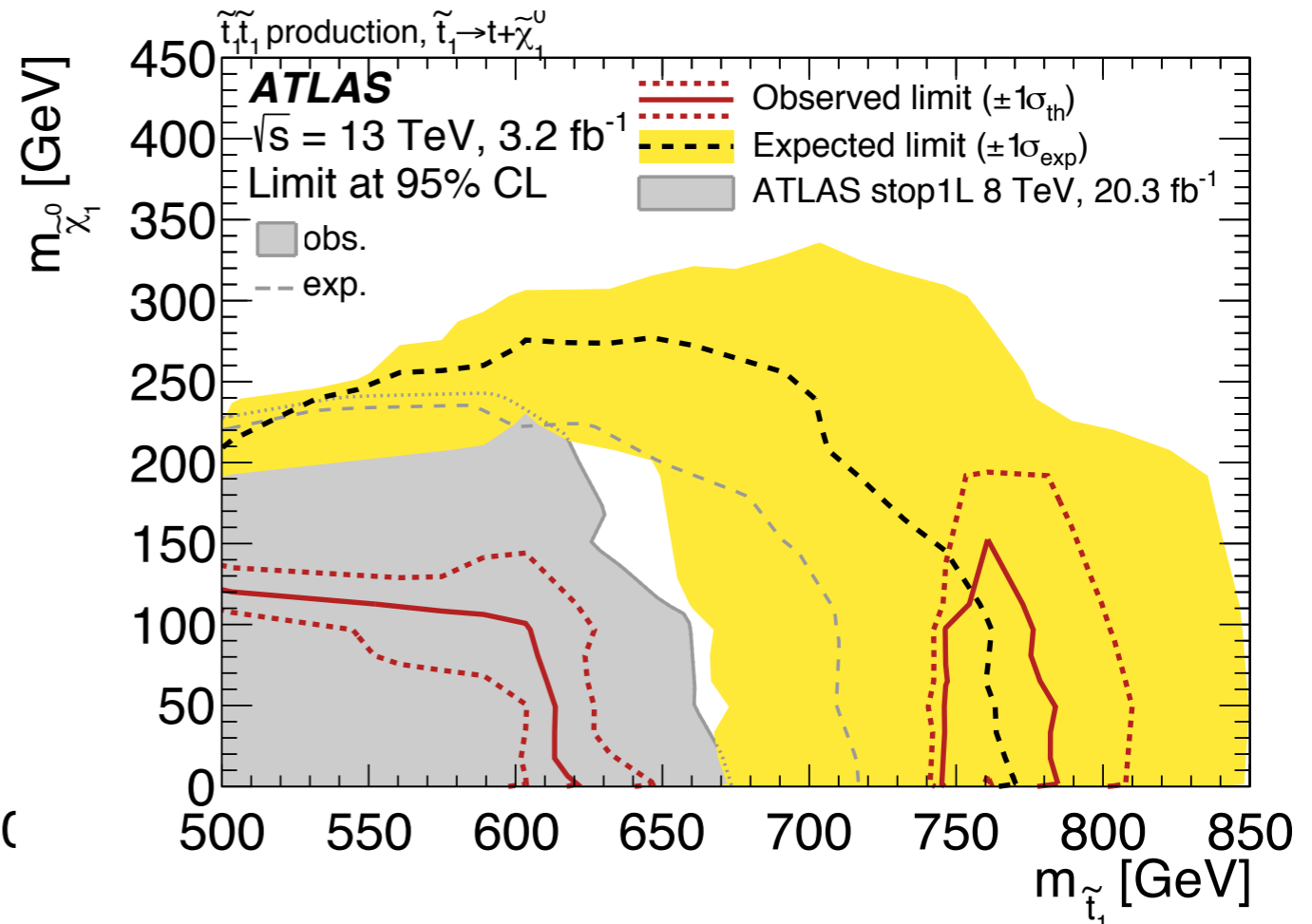
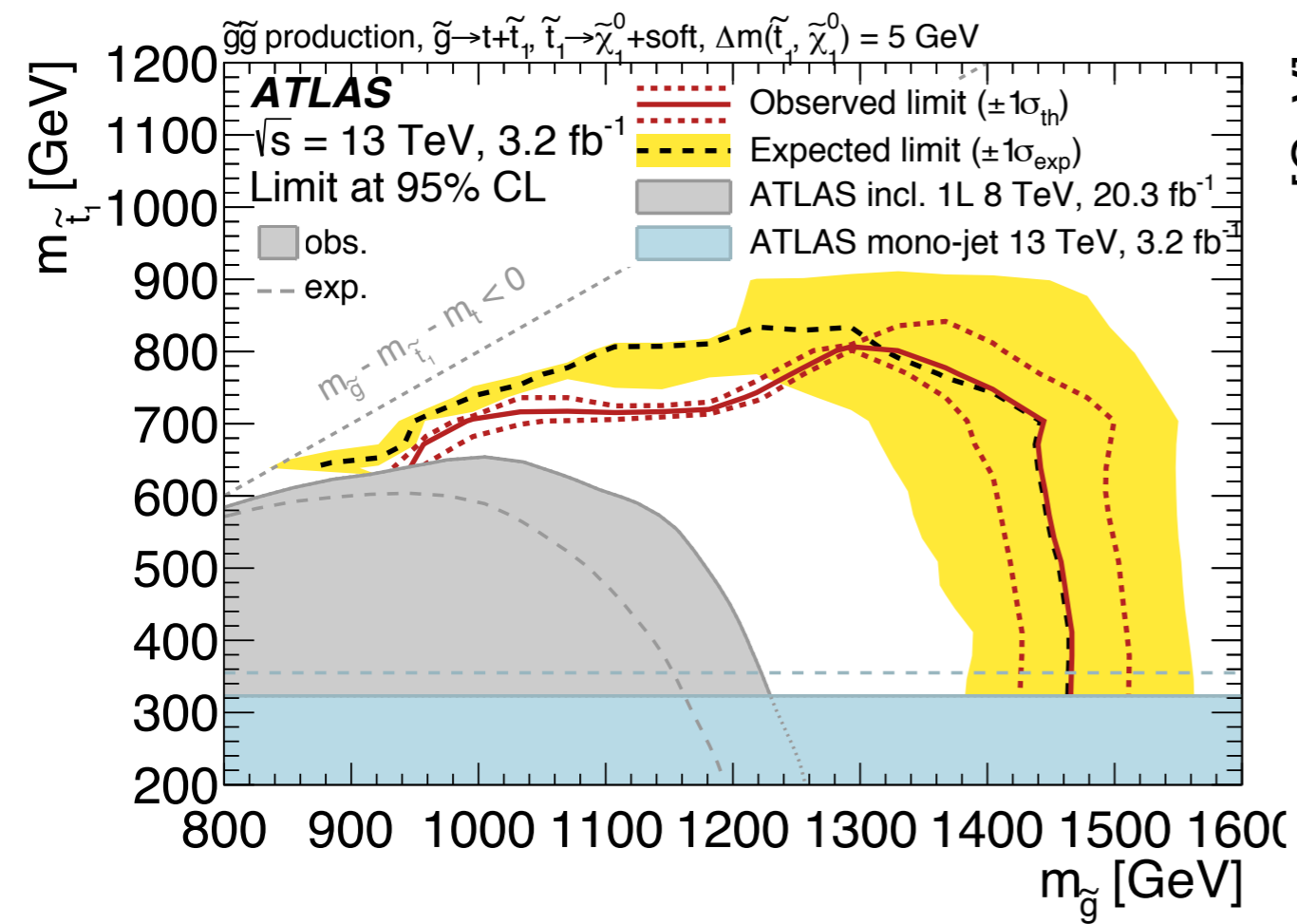
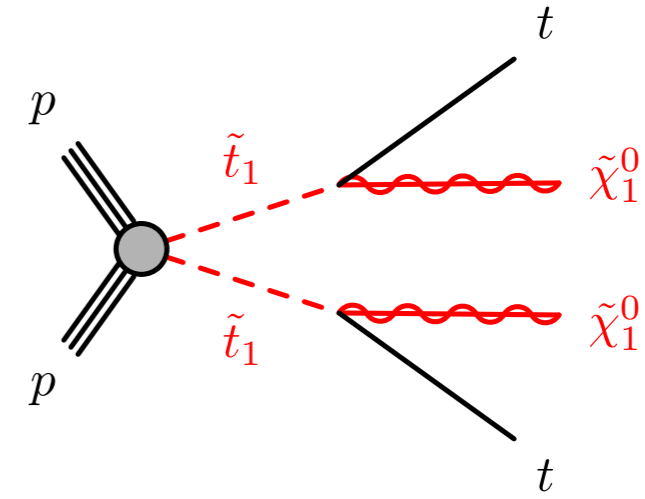
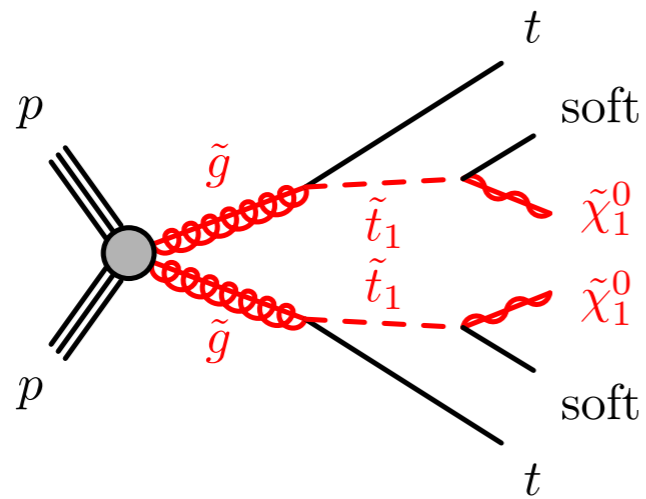
CMS PAS JME-14-002

Rank	Z	Pairs of variables	
1.	38.5 ± 1.6	M_{Prune}	τ_2 / τ_1
2.	37.9 ± 1.6	M_{Filt}	τ_2 / τ_1
3.	37.8 ± 1.6	M_{Trim}	τ_2 / τ_1
4.	37.7 ± 1.6	M_{Trim}	QGL Combo
5.	37.2 ± 1.6	M_{Prune}	QGL Combo
6.	36.7 ± 1.5	$M_{SD} \beta = -1$	τ_2 / τ_1
7.	36.3 ± 1.5	$M_{SD} \beta = 0$	τ_2 / τ_1
8.	35.8 ± 1.5	$M_{SD} \beta = 2$	τ_2 / τ_1
9.	35.3 ± 1.4	$M_{SD} \beta = 1$	τ_2 / τ_1
10.	35.0 ± 1.4	$M_{SD} \beta = -1$	QGL Combo

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Variable	SR1		SR2
≥ 4 jets with $p_T > [\text{GeV}]$	(80 50 40 40)		≥ 4 jets with $p_T > [\text{GeV}]$
E_T^{miss} [GeV]	> 260		E_T^{miss} [GeV]
$H_{T,\text{sig}}^{\text{miss}}$	> 14		$H_{T,\text{sig}}^{\text{miss}}$
m_T [GeV]	> 170		m_T [GeV]
am_{T2} [GeV]	> 175		am_{T2} [GeV]
$topness$	> 6.5		$\Delta R(b, \ell)$
m_{top}^x [GeV]	< 270		$\Delta R(b_1, b_2)$
$\Delta R(b, \ell)$	< 3.0		Number of b -tags
$\Delta R(b_1, b_2)$	–		Leading large-R jet p_T [GeV]
Number of b -tags	≥ 1		Leading large-R jet mass [GeV]
			$\Delta\phi(\vec{p}_T^{\text{miss}}, 2^{\text{nd}} \text{large-R jet})$

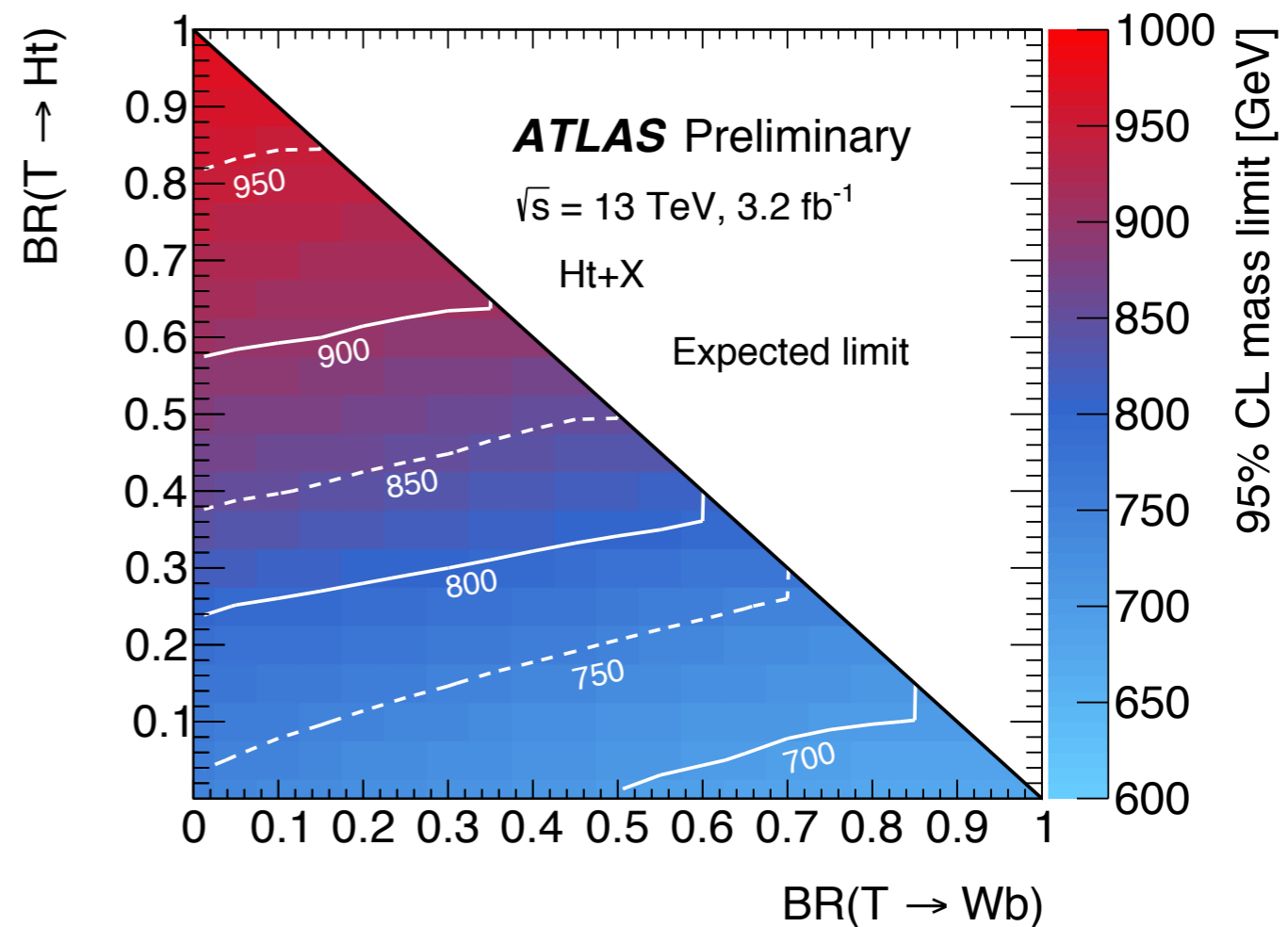
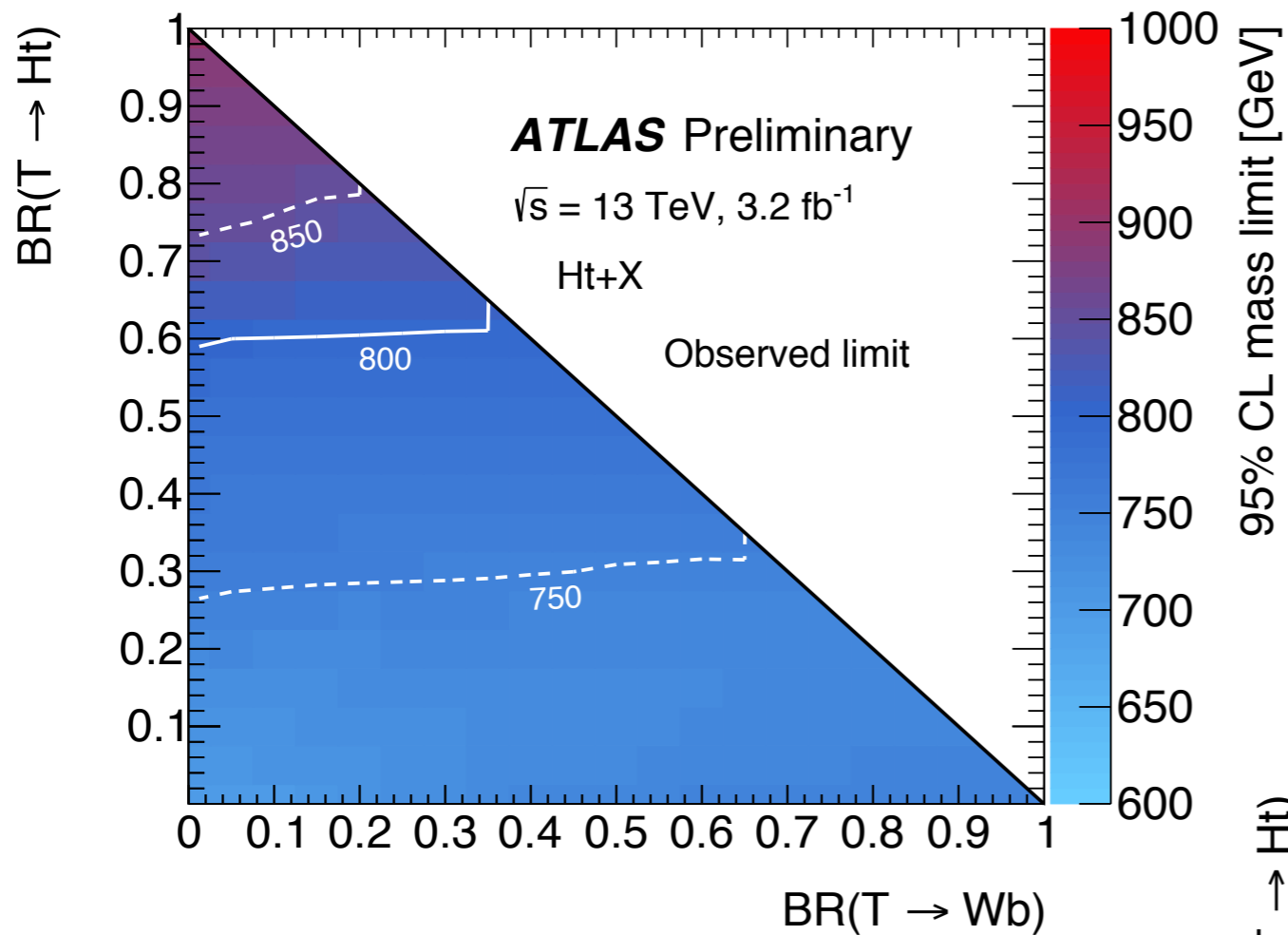
	SR3
≥ 4 jets with $p_T > [\text{GeV}]$	(120 80 50 25)
E_T^{miss} [GeV]	> 480
$H_{T,\text{sig}}^{\text{miss}}$	> 14
m_T [GeV]	> 190
am_{T2} [GeV]	> 175
$topness$	> 9.5
$\Delta R(b, \ell)$	< 2.8
$\Delta R(b_1, b_2)$	–
Number of b -tags	≥ 1
Leading large-R jet p_T [GeV]	> 280
Leading large-R jet mass [GeV]	> 70



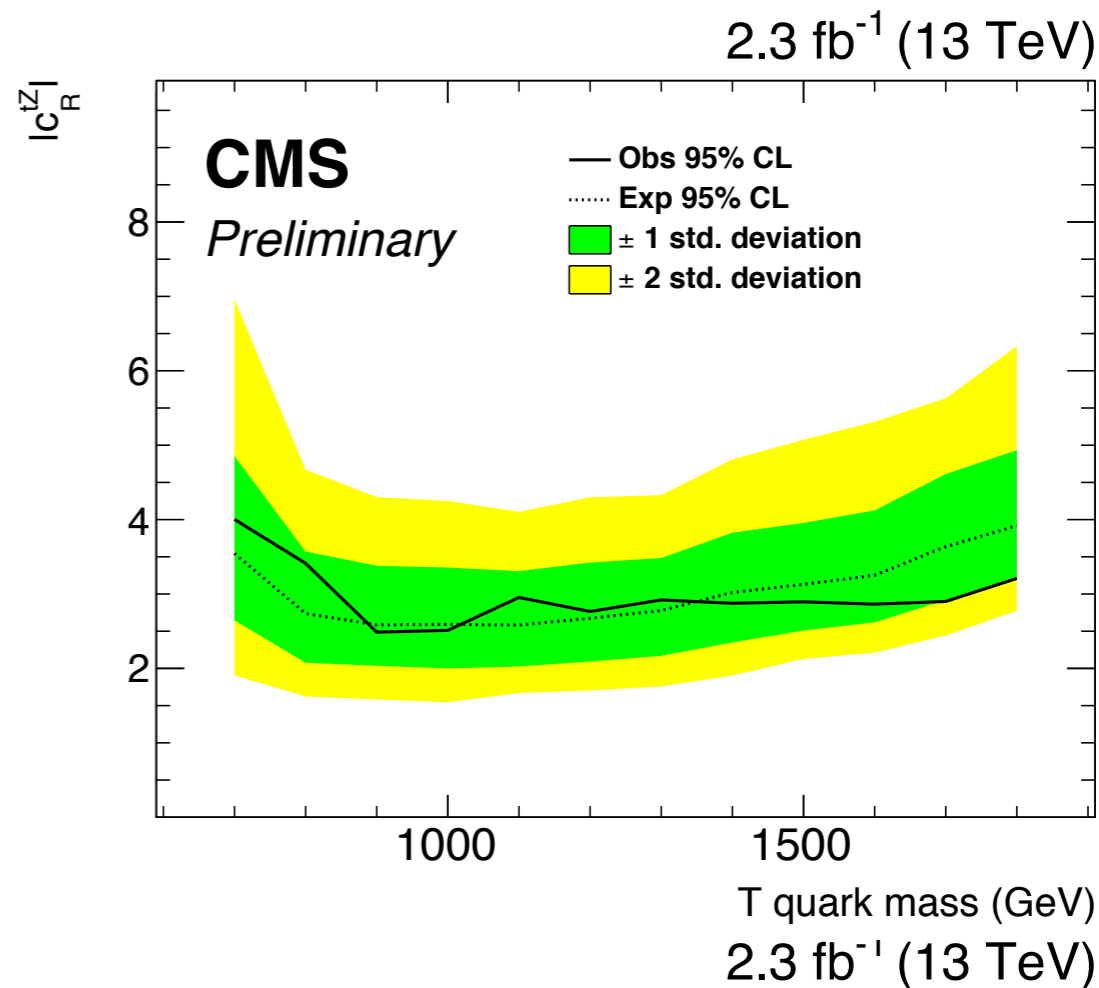
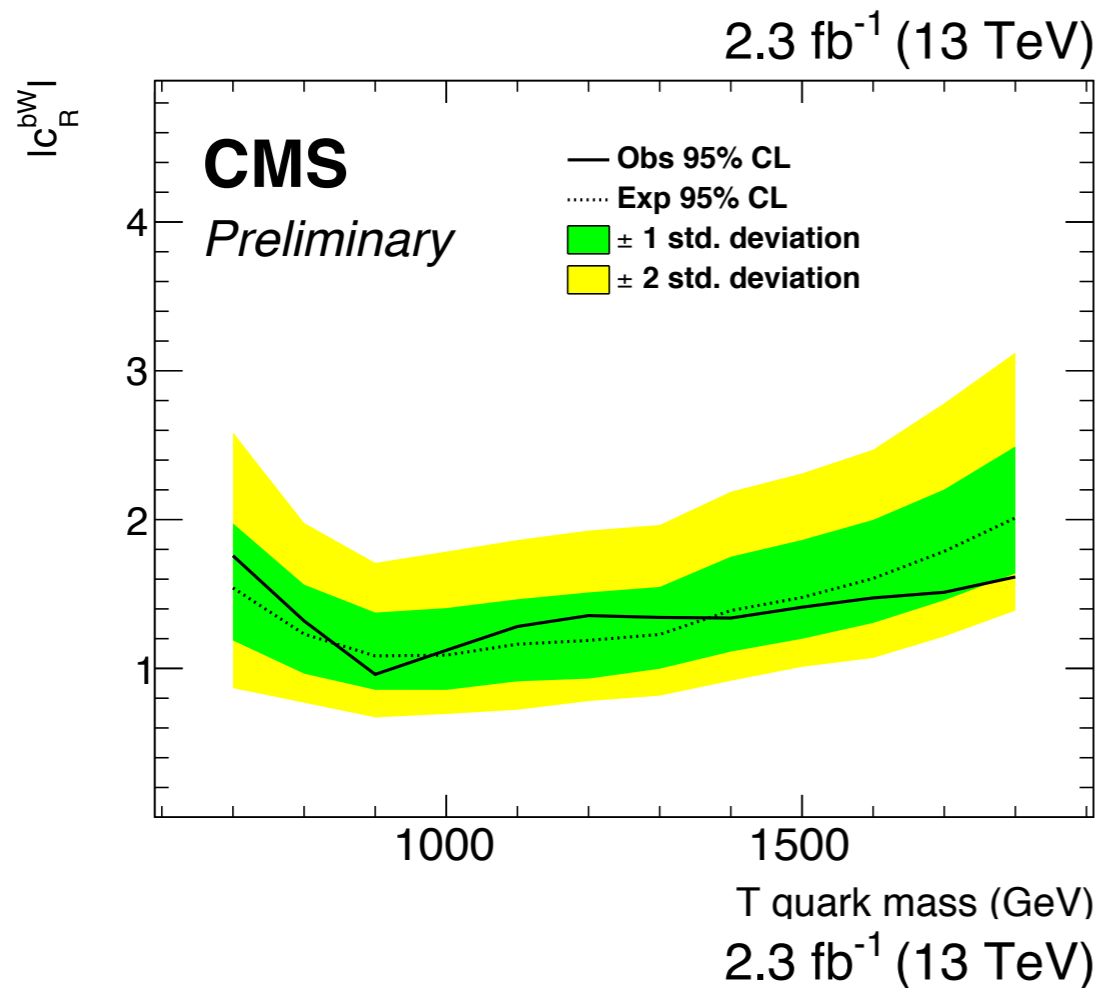
SRI
 dominates

SR2
 dominates

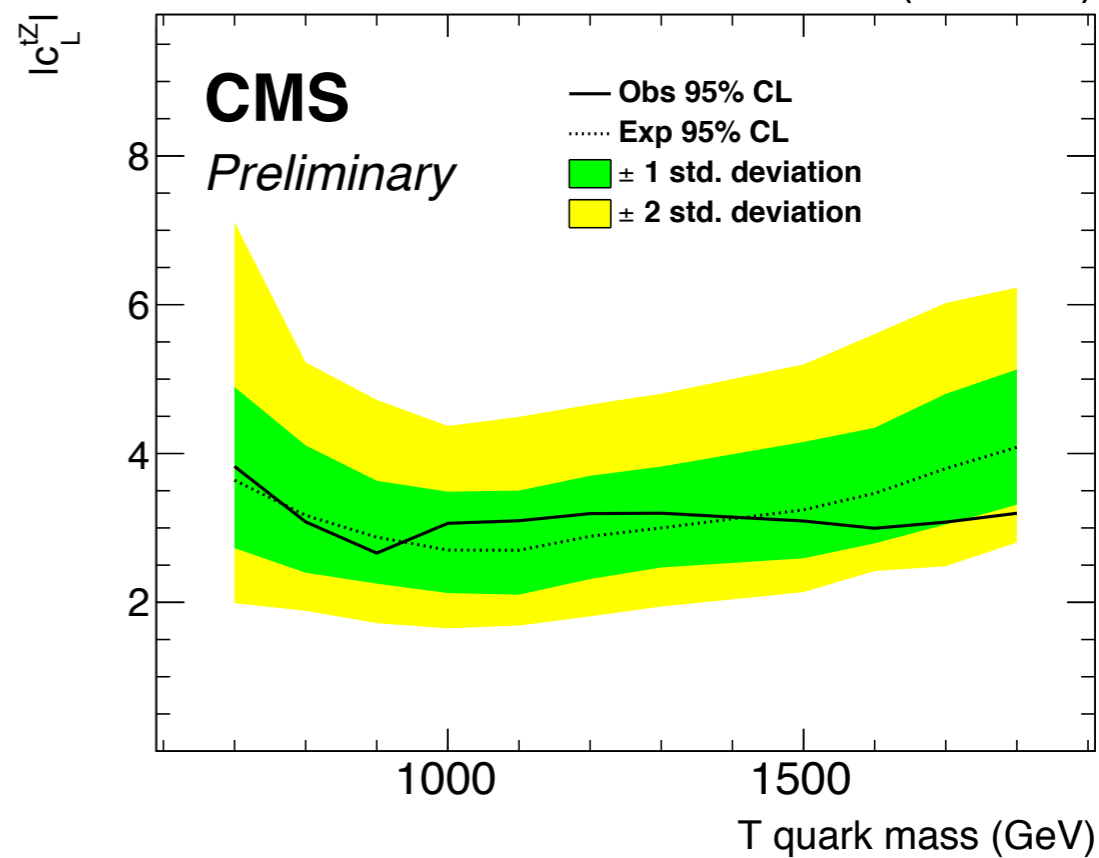
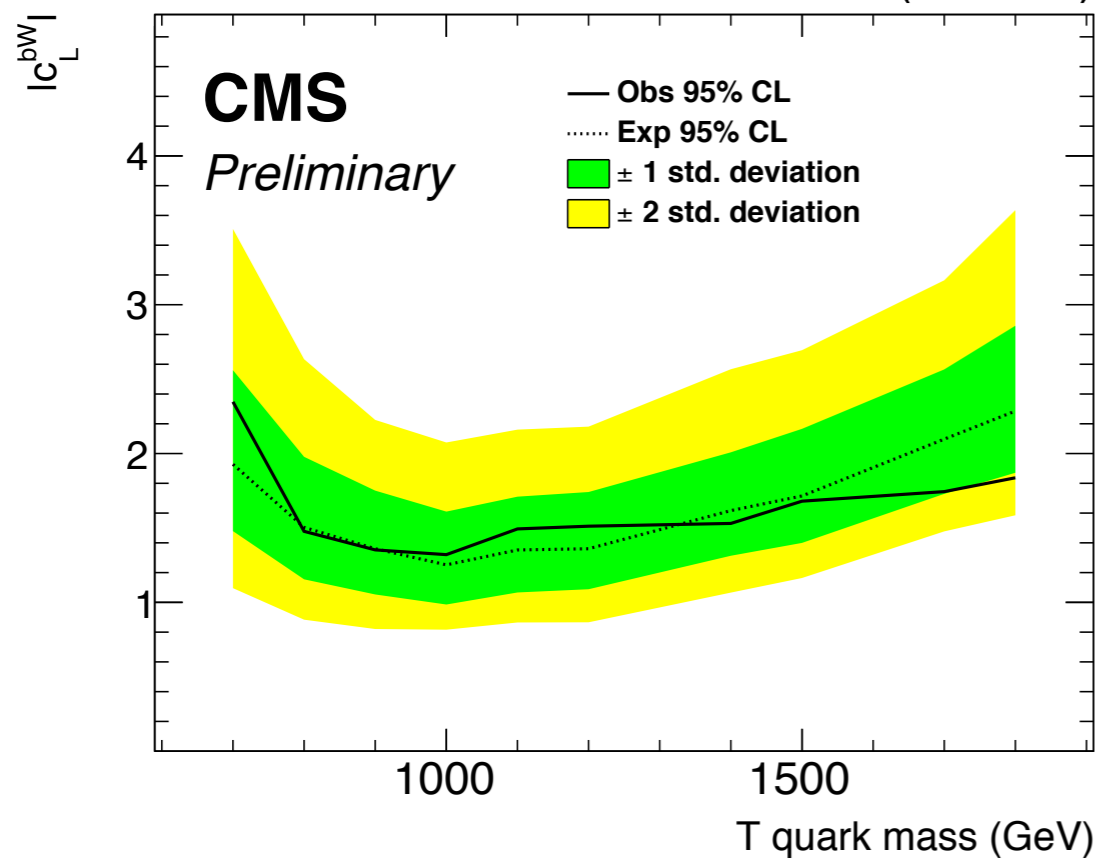
ATLAS-CONF-2016-013



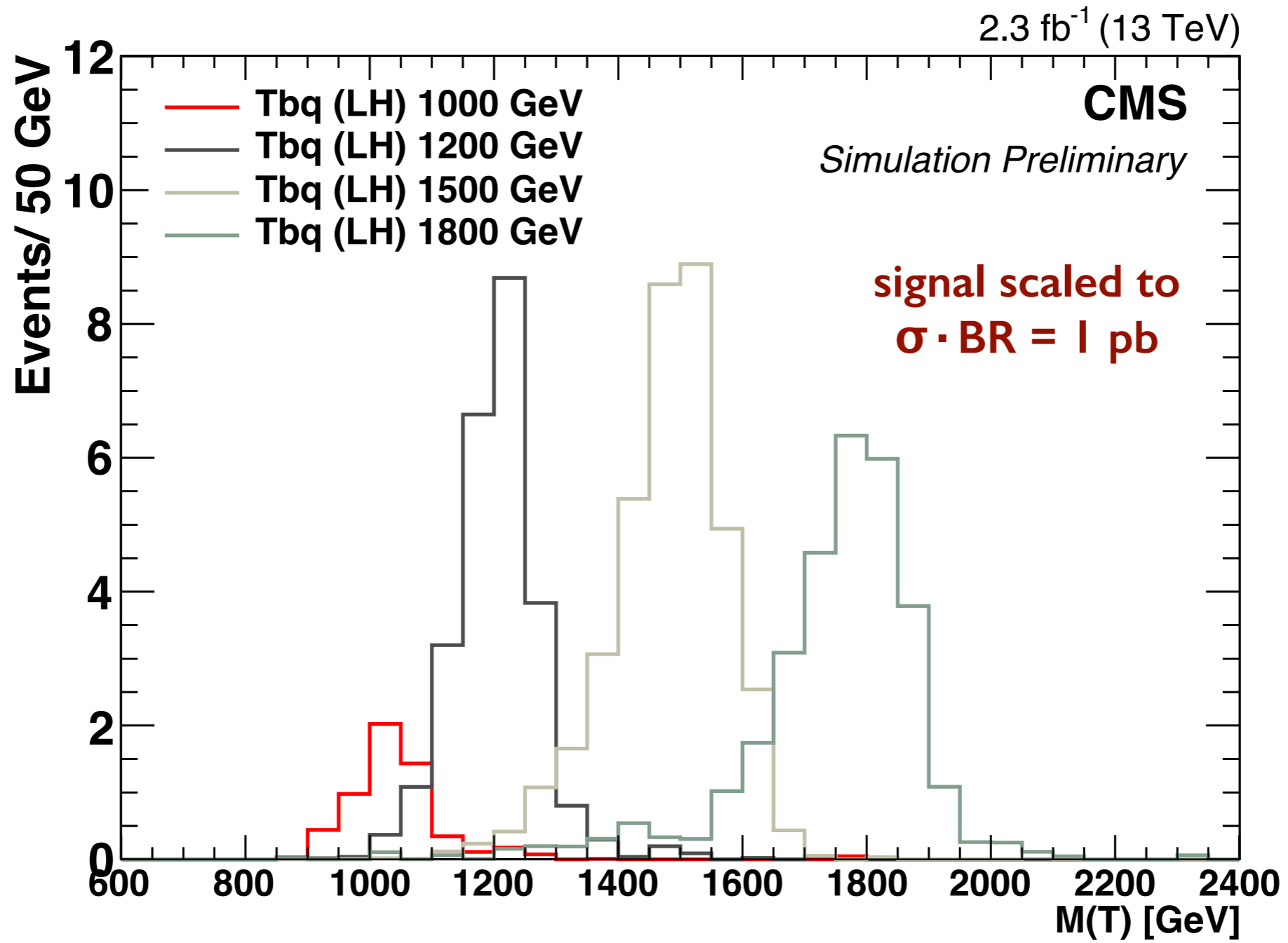
CMS PAS B2G-I5-008



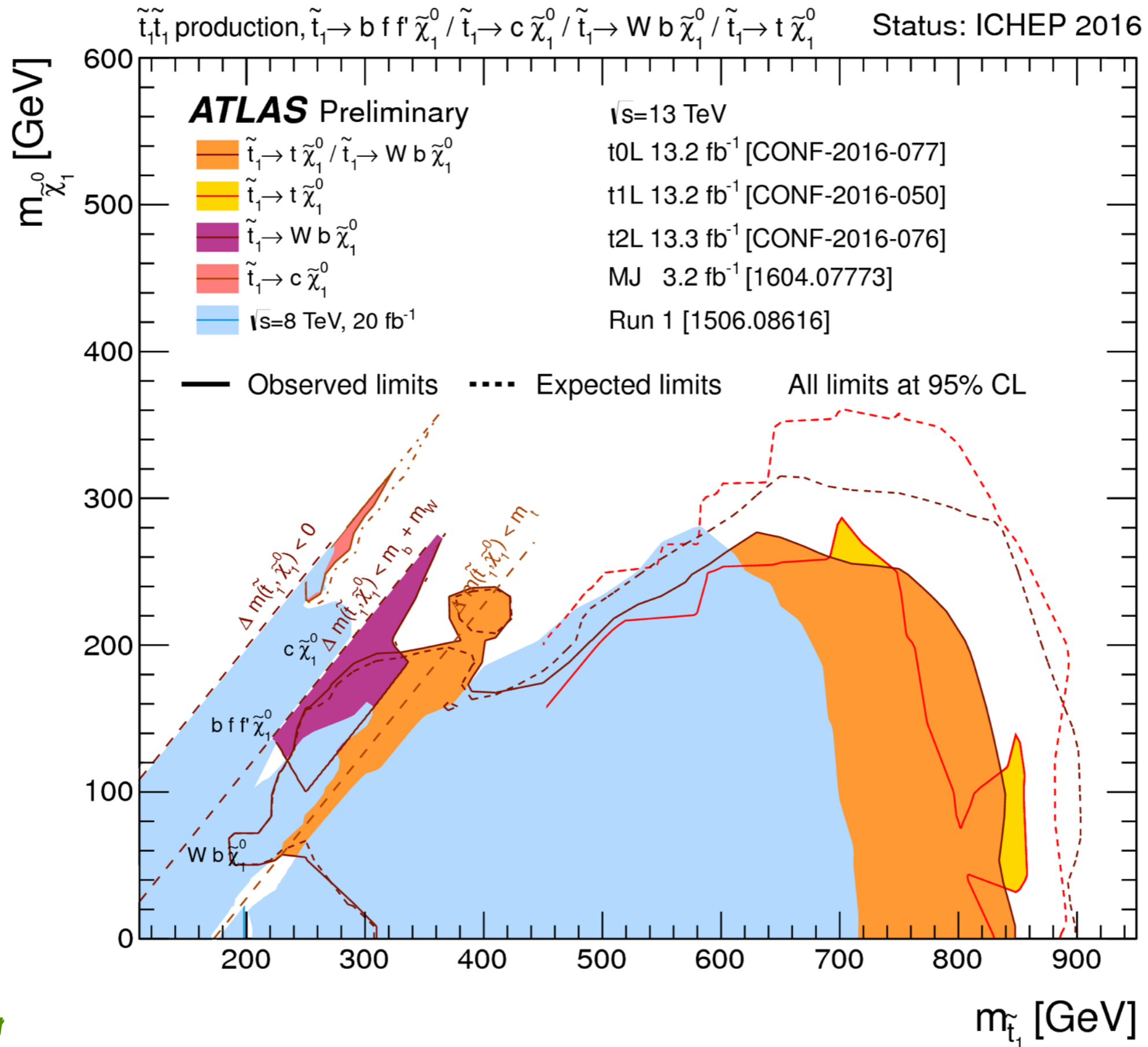
RH



LH



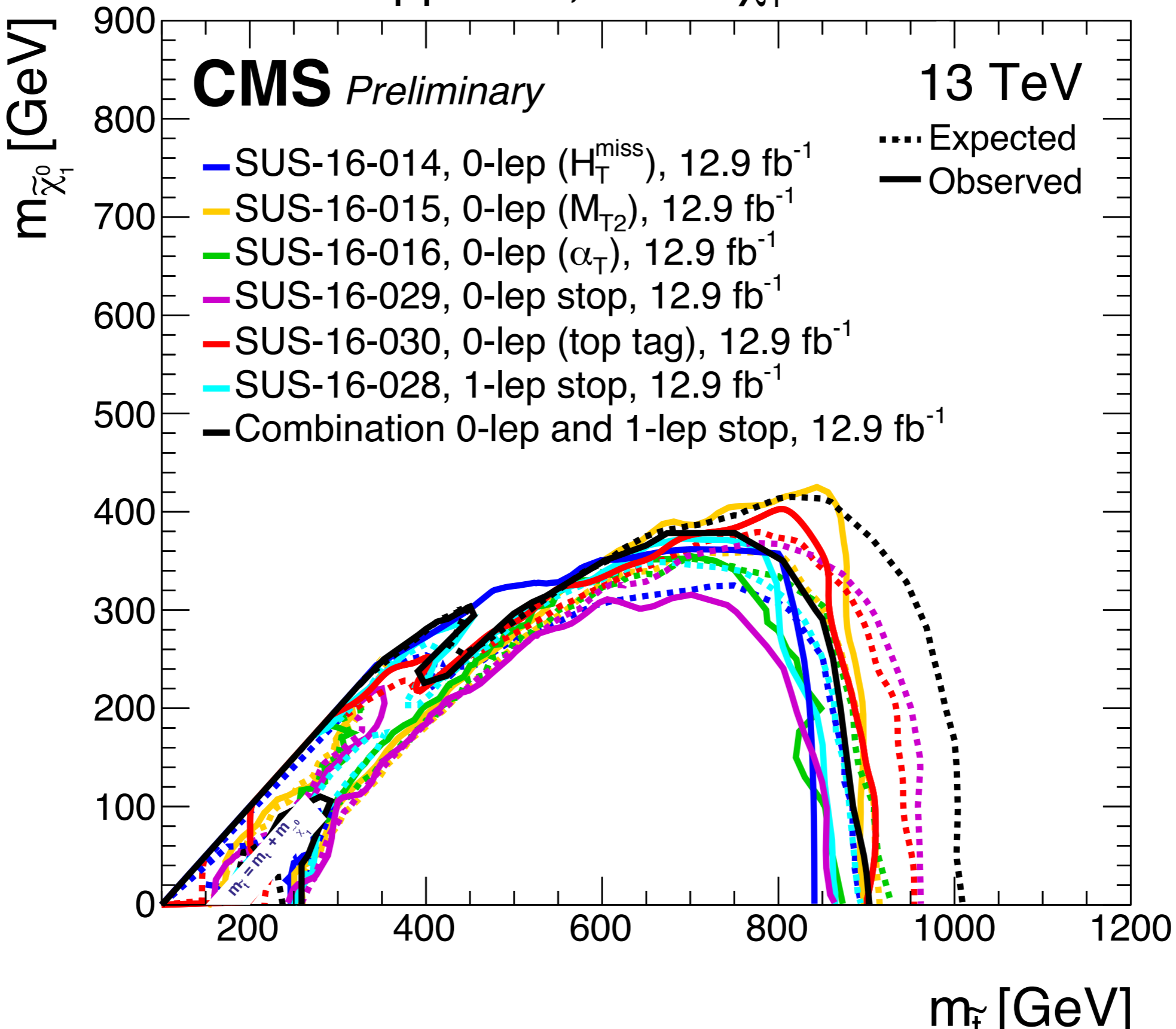
Stop Summary ATLAS



Stop Summary CMS

$$pp \rightarrow \tilde{t}\tilde{t}, \tilde{t} \rightarrow t \tilde{\chi}_1^0$$

ICHEP 2016



ATLAS-CONF-2016-050

Common event selection		
Trigger	E_T^{miss} trigger	
Lepton	exactly one signal lepton (e, μ), no additional baseline leptons	
Jets	at least two signal jets, and $ \Delta\phi(\text{jet}_i, \vec{p}_T^{\text{miss}}) > 0.4$ for $i \in \{1, 2\}$	
Hadronic τ veto*	veto events with a hadronic τ decay and $m_{T2}^\tau < 80$ GeV	
Variable	SR1 $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$	tN_high
Number of (jets, b -tags)	($\geq 4, \geq 1$)	($\geq 4, \geq 1$)
Jet $p_T >$ [GeV]	(80 50 40 40)	(120 80 50 25)
E_T^{miss} [GeV]	> 260	> 450
$E_{T,\perp}^{\text{miss}}$ [GeV]	–	> 180
$H_{T,\text{sig}}^{\text{miss}}$	> 14	> 22
m_T [GeV]	> 170	> 210
am_{T2} [GeV]	> 175	> 175
$topness$	> 6.5	–
m_{top}^χ [GeV]	< 270	–
$\Delta R(b, \ell)$	< 3.0	< 2.4
Leading large-R jet p_T [GeV]	–	> 290
Leading large-R jet mass [GeV]	–	> 70
$\Delta\phi(\vec{p}_T^{\text{miss}}, 2^{\text{nd}} \text{ large-R jet})$	–	> 0.6

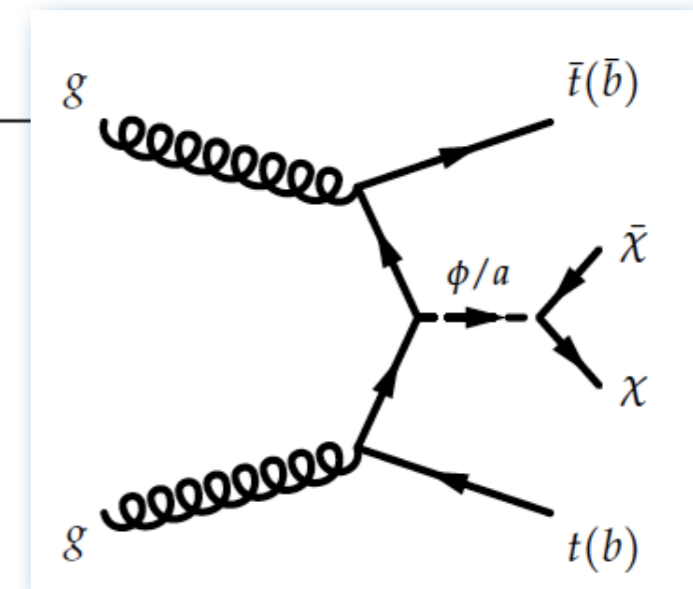
ATLAS-CONF-2016-050

$$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm$$

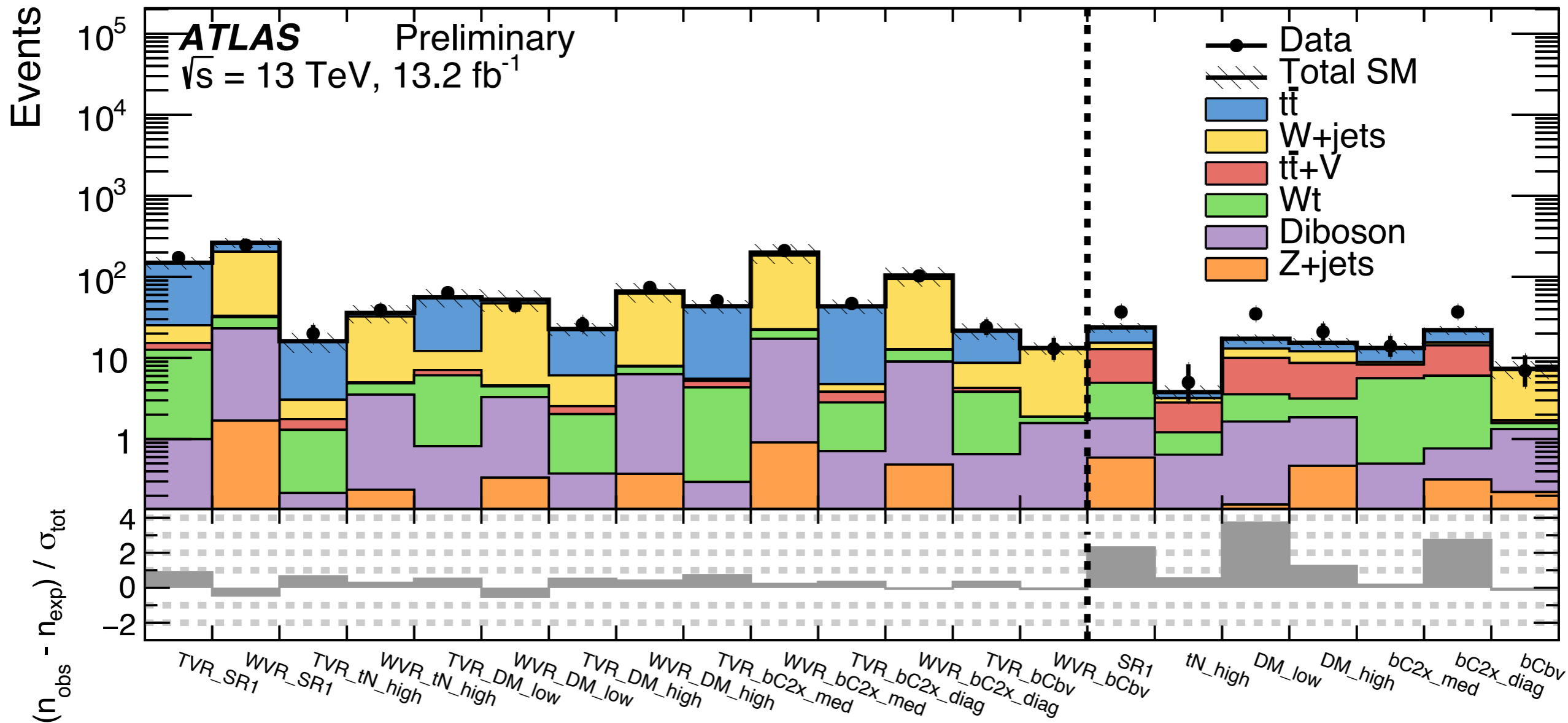
$$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm$$

Variable	bC2x_diag	bC2x_med	bCbv
Number of (jets, b -tags)	($\geq 4, \geq 2$)	($\geq 4, \geq 2$)	($\geq 2, = 0$)
Jet $p_T > [\text{GeV}]$	(70 60 55 25)	(170 110 25 25)	(120 80)
b -tagged jet $p_T > [\text{GeV}]$	(25 25)	(105 100)	–
E_T^{miss} [GeV]	> 230	> 210	> 360
$H_{T,\text{sig}}^{\text{miss}}$	> 14	> 7	> 16
m_T [GeV]	> 170	> 140	> 200
am_{T2} [GeV]	> 170	> 210	–
$ \Delta\phi(\text{jet}_i, \vec{p}_T^{\text{miss}}) (i = 1)$	> 1.2	> 1.0	> 2.0
$ \Delta\phi(\text{jet}_i, \vec{p}_T^{\text{miss}}) (i = 2)$	> 0.8	> 0.8	> 0.8
Leading large-R jet mass [GeV]	–	–	[70, 100]
$\Delta\phi(\vec{p}_T^{\text{miss}}, \ell)$	–	–	> 1.2

Variable	DM_low	DM_high
Number of (jets, b -tags)	($\geq 4, \geq 1$)	($\geq 4, \geq 1$)
Jet $p_T > [\text{GeV}]$	(60 60 40 25)	(50 50 50 25)
E_T^{miss} [GeV]	> 300	> 330
$H_{T,\text{sig}}^{\text{miss}}$	> 14	> 9.5
m_T [GeV]	> 120	> 220
am_{T2} [GeV]	> 140	> 170
$\min(\Delta\phi(\vec{p}_T^{\text{miss}}, \text{jet}_i)) (i \in \{1 - 4\})$	> 1.4	> 0.8
$\Delta\phi(\vec{p}_T^{\text{miss}}, \ell)$	> 0.8	–

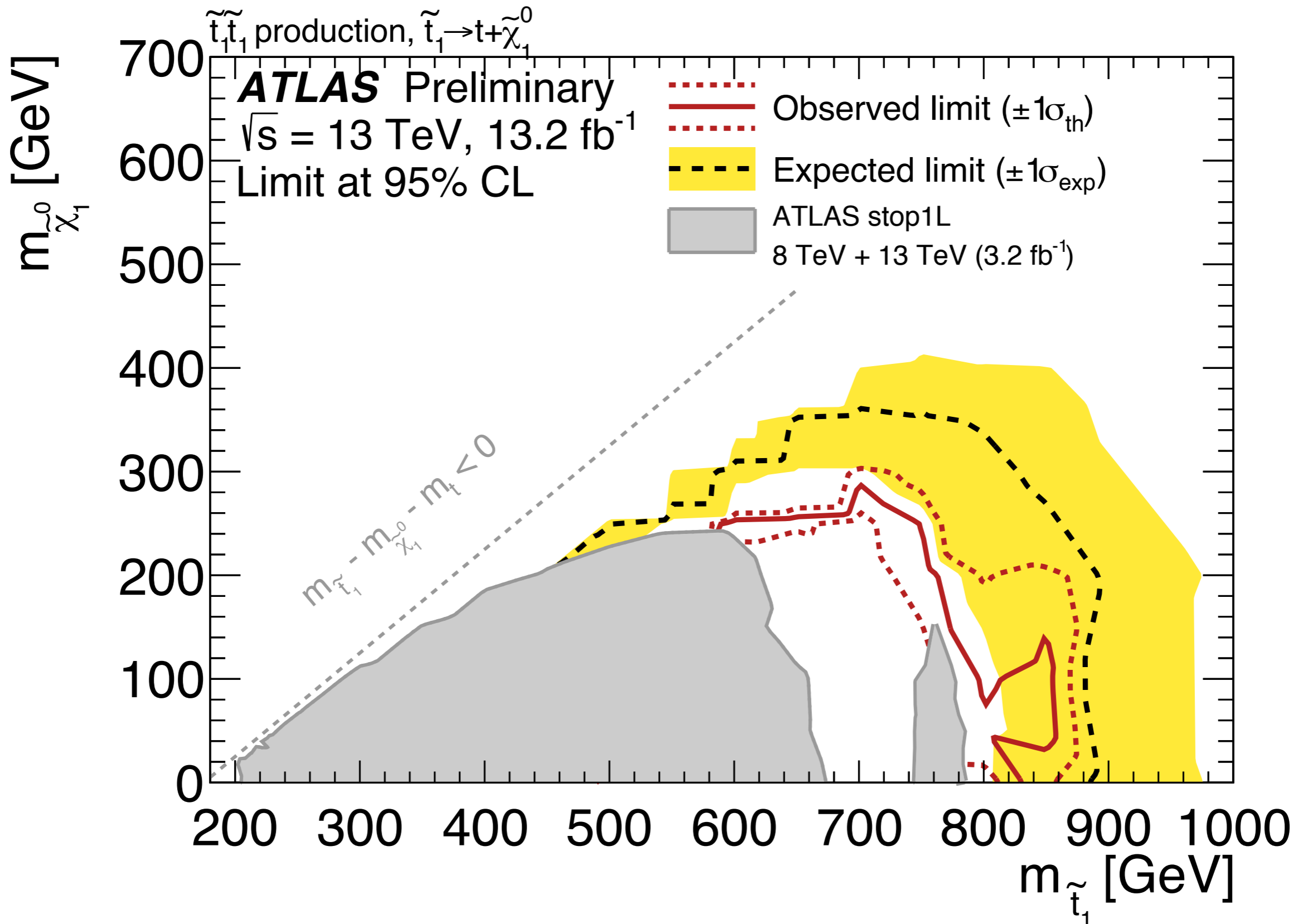


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Signal region	SR1	tN_high	bC2x_diag	bC2x_med	bCbv	DM_low	DM_high
Observed	37	5	37	14	7	35	21
Total background	24 ± 3	3.8 ± 0.8	22 ± 3	13 ± 2	7.4 ± 1.8	17 ± 2	15 ± 2
$t\bar{t}$	8.4 ± 1.9	0.60 ± 0.27	6.5 ± 1.5	4.3 ± 1.0	0.26 ± 0.18	4.2 ± 1.3	3.3 ± 0.8
W +jets	2.5 ± 1.1	0.15 ± 0.38	1.2 ± 0.5	0.63 ± 0.29	5.4 ± 1.8	3.1 ± 1.5	3.4 ± 1.4
Single top	3.1 ± 1.5	0.57 ± 0.44	5.3 ± 1.8	5.1 ± 1.6	0.24 ± 0.23	1.9 ± 0.9	1.3 ± 0.8
$t\bar{t} + V$	7.9 ± 1.6	1.6 ± 0.4	8.3 ± 1.7	2.7 ± 0.7	0.12 ± 0.03	6.4 ± 1.4	5.5 ± 1.1
Diboson	1.2 ± 0.4	0.61 ± 0.26	0.45 ± 0.17	0.42 ± 0.20	1.1 ± 0.4	1.5 ± 0.6	1.4 ± 0.5
Z +jets	0.59 ± 0.54	0.03 ± 0.03	0.32 ± 0.29	0.08 ± 0.08	0.22 ± 0.20	0.16 ± 0.14	0.47 ± 0.44
$t\bar{t}$ NF	1.03 ± 0.07	1.06 ± 0.15	0.89 ± 0.10	0.95 ± 0.12	0.73 ± 0.22	0.90 ± 0.17	1.01 ± 0.13
W +jets NF	0.76 ± 0.08	0.78 ± 0.08	0.87 ± 0.07	0.85 ± 0.06	0.97 ± 0.12	0.94 ± 0.13	0.91 ± 0.07
Single top NF	1.07 ± 0.30	1.30 ± 0.45	1.26 ± 0.31	0.97 ± 0.28	—	1.36 ± 0.36	1.02 ± 0.32
$t\bar{t} + W/Z$ NF	1.43 ± 0.21	1.39 ± 0.22	1.40 ± 0.21	1.30 ± 0.23	—	1.47 ± 0.22	1.42 ± 0.21
p_0 (σ)	0.012 (2.2)	0.26 (0.6)	0.004 (2.6)	0.40 (0.3)	0.50 (0)	0.0004 (3.3)	0.09 (1.3)
$N_{\text{non-SM}}^{\text{limit exp. (95\% CL)}}$	$12.9^{+5.5}_{-3.8}$	$5.5^{+2.8}_{-1.1}$	$12.4^{+5.4}_{-3.7}$	$9.0^{+4.2}_{-2.7}$	$7.3^{+3.5}_{-2.2}$	$11.5^{+5.0}_{-3.4}$	$9.9^{+4.6}_{-2.9}$
$N_{\text{non-SM}}^{\text{limit obs. (95\% CL)}}$	26.0	7.2	27.5	9.9	7.2	28.3	15.6



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